Prospective Observation of CAD/CAM Titanium-Ceramic-Fixed Partial Dentures: 3-Year Follow-Up

Arne F. Boeckler, DMD, Dr Med Dent,[1] Heeje Lee, DDS,[2] Andrea Psoch, DMD,[3] & Juergen M. Setz, DMD, Dr Med Dent Habil[4]

[1] Assistant Professor, Department of Prosthodontics, Martin-Luther-University Halle-Wittenberg, Center for Dentistry and Oral Medicine, Halle, Germany
[2] Associate Professor, Department of Prosthodontics, LSU Health Sciences Center School of Dentistry, New Orleans, LA
[3] Clinical Researcher, Department of Prosthodontics, Martin-Luther-University Halle-Wittenberg, Center for Dentistry and Oral Medicine, Halle, Germany
[4] Professor, Department of Prosthodontics, Martin-Luther-University Halle-Wittenberg, Center for Dentistry and Oral Medicine, Halle, Germany

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Correspondence
Arne F. Boeckler, Martin-Luther-University Halle-Wittenberg—Center for Dentistry and Oral Medicine, Department of Prosthodontics, Grosse Steinstr., 19 Halle (Saale) 06108, Germany.
E-mail: arne.boeckler@medizin.uni-halle.de

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Abstract

Purpose: There is lack of knowledge about the clinical performance of computer-aided design/computer-aided manufacturing (CAD/CAM) titanium-ceramic-fixed partial dentures (FPDs). The purpose of this study was to evaluate CAD/CAM titanium-ceramic FPDs after 3 years in function.
Materials and Methods: Thirty-one FPDs were fabricated for 23 patients. The Ti frameworks were completely fabricated using CAD/CAM technology, and the low-fusing porcelain was veneered. After confirming there were no mechanical or biological complications, the FPDs were cemented using zinc phosphate cement. The patients were recalled at 12, 24, and 36 months after cementation to examine for the presence of any mechanical complications, such as fractures of the veneering porcelain or the supportive framework, or biological complications, including caries, gingivitis, or periodontitis. The periodontal condition was measured using probing depth (PD), bleeding on probing (BOP), and plaque index (PI). Success and survival rates were estimated using the Kaplan-Meier analysis.
Results: There were four cohesive and three adhesive porcelain fractures, but no framework fractured. The Kaplan-Meier cumulative success rate of the CAD/CAM titanium-ceramic crown with regard to mechanical complications was 76.4%, and the cumulative survival rate was 96.8% after 3 years of use. One patient developed caries, but the condition was not associated with marginal discrepancy. No other biological complications were reported. The periodontal parameters demonstrated a tendency that slightly increased up to 24 months and was maintained by 36 months. At the end of the follow-up, PD was 2.86 mm, percentile of surface with BOP was 23.5, and PI was 0.45.
Conclusion: The CAD/CAM titanium-ceramic FPDs survived in the mouths of patients without major complications for 3 years, although the risk of porcelain fracture appeared to be relatively high.

In dentistry, noble metal alloys have a long history of use and have demonstrated long-term clinical success in fixed partial dentures (FPDs) in several studies;[1-5] however, the constantly increasing price of gold has influenced clinicians to seek more affordable alternatives. Titanium has received considerable attention because its biologic and mechanical properties meet the requirements for use as a restorative material at a significantly lower price than the noble metal alloys. Ti has demonstrated excellent biocompatibility, high corrosion resistance, low specific gravity, and appropriate strength.[6-8]

Unfortunately, however, Ti use with the conventional lost-wax technique has several problems. Ti has a significantly higher melting temperature than noble metal alloys, which makes the casting process difficult, and the high affinity of molten Ti for investment materials results in the accumulation of a reactive layer on the casting surfaces.[9,10] Since it was found that the reactive layer compromised the quality of titanium-ceramic bonding,[11,12] several methods, such as modifying air pressure or burn-out temperature, or using different investment materials, have been tested to improve Ti casting procedures.

In the meantime, a totally different approach has been developed for the use of Ti as a restorative material, overcoming its inherent deficiencies.

The initial alternative method used machine duplication and spark erosion techniques.[13] To make a single metal ceramic crown, the external form of the coping was made by copy milling from a Ti rod, with the internal surface processed by spark erosion using a graphite electrode that was also formed by copy milling from a die. To fabricate the framework of an FPD, the finished single units were arranged in the proper spatial relationship, and then joined together using a laser-welding method.[14,15] A special veneering porcelain was developed to be compatible with the Ti framework. First, the porcelain needed to have a low coefficient of thermal expansion, because the coefficient of thermal expansion of Ti is significantly lower than that of a conventional noble metal alloy.[16,17] Second, it needed to be fired at a temperature below 880°C because working at a higher temperature than 880°C resulted in a significant dimensional change of the framework[18] and additional accumulations of the oxide layer during the firing cycles.[11]

The titanium-ceramic FPDs fabricated using the methods described above (copy milling, spark erosion, laser welding, and low-fusing porcelain) have been evaluated in several clinical studies.[15,19-21] In general, the clinical performance of the titanium-ceramic FPDs was optimal, with framework fractures of less than 3%.[19,21] No major biologic complications were reported. Even though the incidence of porcelain fracture was higher than that of conventional noble metal alloy FPDs, the actual number of FPDs that had to be replaced was few.[20]

Later, machined titanium-ceramic restorations were further technically advanced by incorporating computer-aided design/computer-aided manufacturing (CAD/CAM) technology.[22] For the CAD/CAM method, the die on the definitive cast was scanned using either an optical or touch probe scanner to send data to the computer. After digitizing the die, the framework was virtually designed on the computer, based on the acquired data and using system-specific CAD software. Then the electronic file was transferred to the special milling unit to fabricate the framework. Contemporary CAD/CAM systems are able to fabricate not only the single crown coping, but also the metal framework for an FPD of up to 14 units or customized implant abutments.[23,24]

Although CAD/CAM technology seems to promise constant improvement,[25-29] there is still a lack of knowledge about the clinical performance of the CAD/CAM titanium-ceramic FPD. Therefore, the purpose of this clinical study was to evaluate the success, survival rate, and clinical parameters of CAD/CAM titanium-ceramic FPDs after 3 years in function.

Materials and methods

Twenty-three patients (7 men, 16 women) aged between 27 and 69 years (average age 55.3) participated in this clinical study. All patients were in need of at least one FPD. To be included in the study, the candidate abutment tooth for the FPD had to fulfill several clinical criteria determined through medical/dental history taking, as well as clinical and radiographic examinations. These criteria were: (1) a healthy periodontium, (2) a vital tooth or properly implemented root canal treatment, (3) correct position in the dental arch, and (4) a sufficient amount of coronal structure. In addition, balanced occlusal forces on both right and left sides of the oral cavity and a favorable interocclusal relationship were required. Patients with untreated temporomandibular disorders or untreated systemic or infectious diseases were excluded from the study. Pregnant women were also excluded from the study.

The patients were informed about the purpose of the study, the clinical procedures involved, the materials to be used, and the benefits/risks of the study. The requirements of the Helsinki declaration were fulfilled, and patients returned the informed consent. The prospective clinical trial was designed according to the CONSORT recommendations for improving the quality of clinical trials,[30] and was approved by the local Ethical Committee (vote number: 031203). In total, 31 CAD/CAM titanium-ceramic FPDs (1 anterior, 30 posterior) were placed. All treatment procedures were performed by five faculty members of the Department of Prosthodontics, Martin-Luther-University Halle-Wittenberg, Center for Dentistry and Oral Medicine, (Halle, Germany) who had 4 to 6 years of clinical experience. To calibrate the preparation of the abutments, training with special models with artificial and removable teeth (KaVo-Model Basic, KaVo Dental, Leutkirch, Germany) was given. To create equivalent margins, a preparation instrument with a 1.2-mm diameter was used (8837 KR, Brassler, Lemgo, Germany). To guarantee a minimal and reproducible occlusal reduction, a burnishing hand instrument with a 1.6-mm diameter, ball-shaped end (BB186, Hu-Friedy, Chicago, IL) was used as a gauge. Calibration training was given by a senior prosthodontist before the study began. Most were 3-unit (22 FPDs), while four 4-unit, four 5-unit, and one 6-unit FPD were fabricated and placed (a total of 108 units).

The abutment teeth were prepared according to preparation guidelines for conventional metal ceramic restorations. To create a sufficient space for the veneering porcelain at a given minimum thickness of the framework and to avoid overcontoured margins, a circumferential deep chamfer margin (1.2-mm wide) was created, and occlusal reduction of 1.5 to 2 mm was made. After preparation, a complete arch impression was made using a combination of heavy and light-body polyether (Impregum: heavy-body, Permadyne: light-body, 3M ESPE, Seefeld, Germany). Interim FPDs were fabricated using bis-GMA material (Protemp Garant, 3M ESPE) and cemented using temporary cement (TempBond, KerrHawe, Bioggio, Switzerland).

The frameworks of the final FPDs were fabricated using the Everest CAD/CAM System (KaVo). The impression was poured in a special type IV dental stone (Everest Rock, KaVo). After separation from the impression, the definitive cast was trimmed and scanned using a special, coded-light charge-coupled device camera (Everest Scan, KaVo). The software (Everest Design Sherpa, KaVo) automatically captured the preparation margin and the die surface. The dental laboratory technician designed the framework, including the pontics, using software. It was decided to make the framework with a 0.5-mm thickness, as commonly used for conventional metal-ceramic restorations.[31] Following the manufacturer's recommendations, the cross-sectional area of the framework connector joint was set to be at least 5 mm^2 (average height: 2.8 mm, width: 2.4 mm). The final data were transferred to the 5-axis

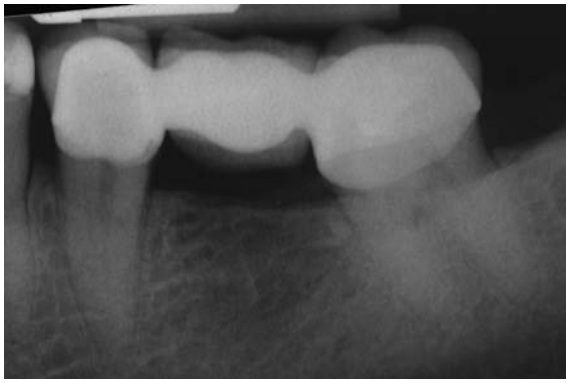

Figure 1 Radiograph showing unsupported porcelain on marginal ridge area.

milling unit (Everest Engine, KaVo) so the framework could be made by milling a grade 2 titanium blank (Everest T-Blank, KaVo).

Before porcelain build-up, the framework fit was evaluated intraorally using a dental explorer (EXS3A6, Hu-Friedy) and fit-checking silicone material (Fit Checker, GC, Tokyo, Japan). Once the fit was confirmed as satisfactory, the framework was conventionally veneered with low-fusing porcelain (Vita Titanium Porcelain, Vita Zahnfabrik, Bad Säckingen, Germany). The restorations in the visible area (up to the second premolar) were fabricated with the buccal porcelain butt margin. As a result, 41 retainers were made with the buccal porcelain butt margin, whereas 26 were made with the metal margin. At the time of delivery, proximal contacts and occlusion were adjusted as needed. It was confirmed that all restorations were free of any technical problems such as a crack or other defect on the veneering porcelain. The fit of the final FPD to the abutment teeth was also investigated intraorally using a dental explorer (EXS3A6) and fit-checking silicone material (Fit Checker). The FPDs were cemented using zinc phosphate cement (Harvard, Richter & Hoffmann, Berlin, Germany).

Immediately after cementation, periodontal probing depth (PD), bleeding-on-probing (BOP), and plaque index[32] (PI) of the abutment teeth were measured. The follow-up examinations consisted of clinical and photographic examinations of the FPDs. Radiographic examinations (Fig 1) were taken to examine the possible periapical radiolucency. If apical radiolucency was suspicious, additional radiographs from different angles were taken.

At 12, 24, and 36 months after cementation, patients were recalled, and the restorations were examined for mechanical and biological complications by two calibrated faculty members of the Department of Prosthodontics with 4 to 6 years of clinical experience. Calibration training was given and approved by a senior prosthodontist before the study began. Follow-up evaluations included clinical, radiographic, and clinical photographic examinations. A new, practical classification was introduced for evaluation of mechanical failures of the veneering porcelain, as follows: Class I: a minute crack visible by changing the direction of the light source; Class II: a clear fissure with discoloration; Class III: chipping within the body of porcelain; and Class IV: porcelain flaking with metal framework exposure. Any other mechanical complications of the FPDs were observed and reported. Biological complications such as secondary caries, periapical radiolucency, and loss of tooth vitality were observed and reported if found. Periodontal parameters (PD, BOP, PI) were measured for comparison with parameters at baseline. Finally, maxillary and mandibular impressions were made using irreversible hydrocolloid (Palgat Plus, 3M ESPE) to fabricate diagnostic casts.

The FPD was categorized as "success" if it was free from any mechanical and biological complications, while it was categorized as "survival" if it was functioning in place with complication(s), but not replaced. The success and survival rates were estimated using the Kaplan-Meier analysis with 95% confidence intervals.

Results

During the 3-year follow-up, veneering porcelain fractures occurred on seven FPDs (four cohesive, three adhesive fractures) resulting in replacement of one FPD due to loss of function and esthetics (Fig 2). The fractures occurred in seven patients, meaning none of the seven FPDs had more than one fracture. Six fractures were found on the abutments and one fracture on the pontic. All fractures occurred on posterior teeth. No framework fracture was observed during the 3 years.

As to the biologic complications, one patient developed root caries on an abutment tooth of the FPD, not associated with marginal discrepancy. Since the carious lesion was away from the FPD margin, it was completely removed, and the tooth restored using a composite resin filling material (Tetric Ceram, Ivoclar Vivadent, Ellwangen, Germany) without replacing the entire FPD. The mean of PD constantly increased from 2.17 mm (baseline) to 2.86 mm (36 months), but the increase of PD from 24 to 36 months was only 0.03 mm (Table 1). The mean of PI and the percentage of surfaces with BOP also appeared to increase in the beginning, but the increase stopped at either 12 months (BOP) or 24 months (PI).

At the 24-month recall, four patients (six FPDs, all posterior) were lost to follow-up due to medical conditions or address changes. Therefore, the Kaplan-Meier cumulative success rate

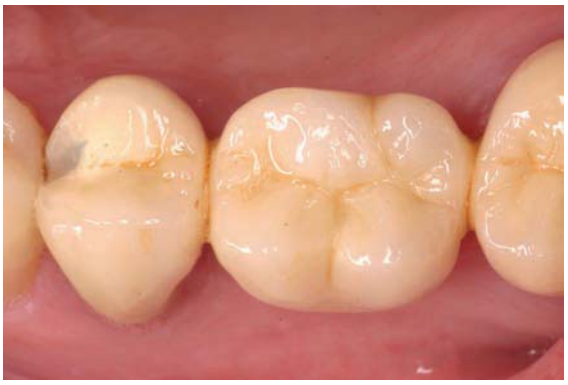

Figure 2 Clinical photograph showing veneering porcelain fracture on marginal ridge of abutment.

Table 1 Results of periodontal examinations

Parameter	Baseline (n = 41)	12 months (n = 37)	24 months (n = 37)	36 months (n = 36)
Probing depth mean (mm)	2.17	2.37	2.83	2.86
Percentage of surface with bleeding on probing	17.5	27.6	25.0	23.5
Plaque index mean	0	0.46	0.49	0.45

of the CAD/CAM titanium-ceramic crown with regard to mechanical complications was 76.4% (95% confidence interval: 62.4% to 93.5%) (Fig 3), and the cumulative survival rate was 96.8% (95% confidence interval: 90.8% to 100%) (Fig 4) after 3 years of use.

Discussion

At the 3-year follow-up examinations, although it was observed that the majority of the CAD/CAM FPDs survived without any complications, seven FPDs experienced minor veneering porcelain defects. Depending on the severity and/or location of the porcelain fracture, the survival of the FPD was determined. Fortunately, all problems but one could be solved by simple polishing or repair using a self-etching bonding system (Clearfil SE Bond, Kuraray, Tokyo, Japan) and a silane coupling agent (Clearfil Porcelain Bond Activator, Kuraray) in combination with a composite resin material (Tetric Ceram, Ivoclar Vivadent). To serve in the mouths following the incidents, the results of the modification were approved by the patients in terms of function and esthetics. The one prosthesis that required removal displayed loss of function and esthetics with significant cohesive porcelain failure (Class III), and it was determined that repair would not be predictable. Once the intraoral modifications were performed, no further mechanical complications were found from the same FPDs.

To determine the reasons for the porcelain fracture, patient factors were investigated carefully in those instances of mechanical complications in the FPDs. No patient was found to have parafunctional habits such as clenching, bruxism, etc. In fact, a patient with those parafunctional habits would not have been accepted for the study according to the inclusion criteria. Therefore, as the porcelain fracture occurred under the range of normal occlusal forces, it was speculated that two problems may have occurred. First, the overall mechanical properties of the low-fusing porcelain, including the strength of the bond to the titanium framework, may not have been strong enough to resist the occlusal force. There were four cohesive and three adhesive porcelain fractures. Cohesive fracture could have occurred if the mechanical resistance of the porcelain against the occlusal force was not high enough, or if the porcelain was veneered including some voids or flaws that could have served as the source of crack initiation. On the other hand, adhesive fracture could have occurred due to insufficient bond strength between the veneering porcelain and the Ti framework. In an earlier clinical report,[33] the experimental low-fusing porcelain was tested on the conventionally fabricated (lost-wax technique) Ti FPD frameworks for 3 years. The incidence of porcelain fracture was extremely high (41%), and the authors speculated mismatch of thermal expansion between the porcelain and metal alloy could be the main reason for the failures by observing the cracks during the porcelain veneering process. Several years later, Walter et al[20] reported the results from their clinical study in which copy-milled titanium-ceramic FPDs were compared with conventional gold alloy metal ceramic FPDs. The Kaplan-Meier survival rate with regard to the porcelain fracture was 84% for Ti FPDs and 98% for conventional high noble FPDs.

Several studies have investigated physical properties of low-fusing porcelain, and the mixed results might explain why the survival rate could not be as high as that of the conventional gold alloy FPDs. Esquivel et al[34] reported that the flexural strength of low-fusing porcelain ranged from 130 to 142 MPa, which exceeded the ADA Specification. Kontonasaki et al[35] reported that the fracture toughness of low-fusing porcelain (0.69 $MPa \cdot m^{1/2}$) was significantly lower than that of high-fusing porcelain (0.81 $MPa \cdot m^{1/2}$); however, microhardness of these two porcelains was not significantly different from each other (approximately 4.5 GPa). Clelland et al[36] reported that

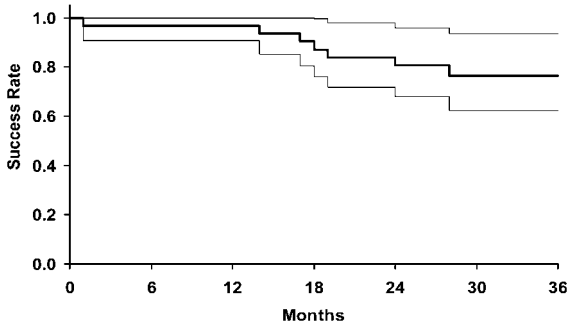

Figure 3 Kaplan-Meier cumulative success rate with 95% confidence interval of CAD/CAM titanium-ceramic FPD for 3 years.

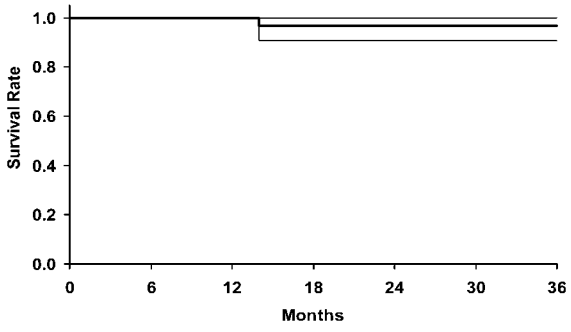

Figure 4 Kaplan-Meier cumulative survival rate with 95% confidence interval of CAD/CAM titanium-ceramic FPD for 3 years.

the wear of opposing enamel was not significantly different between low-fusing and traditional porcelain. Bond strength between Ti and low-fusing porcelain has been an important topic of some studies. It was reported that bonding agent application increased the shear bond strength from 18.7 MPa (control) to 22.6 MPa,[37] and airborne particle abrasion increased from 13.8 MPa to 22.2 MPa;[38] however, the results were still significantly lower than the shear bond strength between gold alloy and traditional porcelain (51.2 MPa).[39] Overall, it appears that further improvements of low-fusing porcelain and its bonding to the Ti surface are still necessary for the CAD/CAM titanium-ceramic FPDs to obtain clinical outcomes comparable to the conventional high noble metal ceramic FPDs.

Second, the capacity for virtual design of the current CAD/CAM system should be taken into consideration. As described earlier, the fabrication technique for the titanium-ceramic FPD has evolved from conventional lost-wax casting to a combination of copy milling, spark erosion, laser welding, and low-fusing porcelain; however, the cumulative success rate of the present study (76.4%) was not as high as that of the copy milling technique of Walter et al[20] Even though the newly developed CAD/CAM system was a state-of-the-art tool when this study began, it could not have been perfect in all aspects. The main concern with the system was that it did not have the full capability to design the retainer and framework in the anatomic forms. In other words, the retainer was only made with an even thickness of 0.5 mm all around. The pontic design was selected from a software library in accordance with the external contour of the retainers. Consequently, in some areas, the veneering porcelain was placed without proper metal support and was subject to irresistible shear forces that may have caused the porcelain fracture. On the other hand, the copy milling technique simply copied the physically fabricated pattern that could have had more anatomic forms to provide even thickness for the veneering porcelain. Fortunately, CAD/CAM technologies have constantly evolved to overcome such limitations, and today's systems are able to either virtually design the retainer with anatomic form or scan the prefabricated anatomic framework patterns to completely mill without spark erosion procedure.

It was found that the periodontal parameters increased in the beginning; however, it did not appear that the restorations actually caused deterioration of periodontal health in that the increase of the parameters stopped before reaching 36 months and were all maintained within clinically acceptable limits. For example, the maximum mean PD was 2.86 mm. The effect on the periodontal tissues of the placement of titanium-ceramic restorations was also reported in an earlier study with a similar outcome showing increased PD within normal limits.[21]

It is anticipated that with the refinement of these technologies, CAD/CAM will take on a major role in restorative dentistry in the near future, because it has shown multiple merits. It can produce a metal framework in faster, simpler, and more economical ways than the conventional lost-wax technique. One could argue that milling a block would result in a large waste, considering the actual amount of metal that remains to be used as the framework after the milling process; however, since CAD/CAM uses base metal blocks, the cost is still significantly less than casting high noble alloys. In terms of the accuracy of the CAD/CAM, this study did not find any crown margins with unacceptable discrepancies. Although one patient developed caries, it did not appear to be associated with marginal accuracy, but rather because the patient maintained poor oral hygiene in the entire mouth.

Being able to mill multiple units with optimal accuracy as shown in this study is also meaningful. With the previous techniques using copy milling and spark erosion, laser welding had to follow that process to finish the multiple-unit framework, resulting in a joint area that was the weakest link of the entire framework and in which fractures often occurred as previously reported.[19,21] Using CAD/CAM, once the framework is designed with the proper thickness, milling a flawless homogenous metal blank without any joint should provide adequate strength, as was demonstrated in this study in which no framework fracture occurred. In addition, the accuracy of a long-span framework may be better with CAD/CAM than with the conventional casting method. The quality of casting largely depends on the skill of the laboratory technician and procedural errors from the wax-up to casting cannot be completely eliminated. Consequently, the clinician sometimes needs to cut and solder the framework at the time of try-in. In contrast, CAD/CAM is a standard process implemented by a machine, and there is no expansion and/or shrinkage of the metal. When the accuracy of CAD/CAM is no longer in doubt, the next question will be how to obtain the most accurate impressions. The current CAD/CAM framework is just as accurate as the master cast, because the machine scans the master cast. If there is discrepancy between the cast and the mouth, however, the framework will not fit accurately in the mouth. Even worse, Ti is not friendly to the conventional soldering procedure, which could be a problem for the correction of a misfit. Today, digital impression technologies are emerging in dentistry and may be the last linkage for the CAD/CAM system to complete the entire sequence from mouth to framework fabrication with the highest accuracy.

When the results of this study are applied to daily practice, care should be taken due to some limitations of the study design. First, the study was designed as a prospective observation without a control group, which allowed only indirect comparison with other similar restorative systems through literature review. Second, 3 years may not be long enough to completely understand the clinical behaviors of the CAD/CAM titanium-ceramic FPDs. Third, as the sample size was not large enough, the results were all combined regardless of position (anterior or posterior) or number of units (3 to 6 units).

As reported earlier, the fully CAD/CAM-milled titanium-ceramic FPDs demonstrated optimal clinical results in terms of survival rate; however, the relatively higher risk of porcelain fracture appeared to be a concern. Therefore, with the help of updated CAD software, it will be necessary to perform a further clinical study that observes CAD/CAM FPDs with an anatomic framework to determine if the risk can be reduced.

Conclusions

Within the limitations of the present clinical observations, it can be concluded that CAD/CAM titanium-ceramic FPDs survived in the patients' mouths without major complications for 3 years; however, the risk of porcelain fracture was relatively high. The

FPDs did not compromise biological parameters during the observation period.

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