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Fracture analysis of randomized implant-supported fixed dental prostheses

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Abstract

Objective—Fractures of posterior fixed dental all-ceramic prostheses can be caused by one or more factors including prosthesis design, flaw distribution, direction and magnitude of occlusal loading, and nature of supporting infrastructure (tooth root/implant), and presence of adjacent teeth. This clinical study of implant-supported, all-ceramic fixed dental prostheses, determined the effects of (1) presence of a tooth distal to the most distal retainer; (2) prosthesis loading either along the non-load bearing or load bearing areas; (3) presence of excursive contacts or maximum intercuspation contacts in the prosthesis; and (4) magnitude of bite force on the occurrence of veneer ceramic fracture.

Methods—89 implant-supported FDPs were randomized as either a three-unit posterior metal-ceramic (Au-Pd-Ag alloy and InLine POM, Ivoclar, Vivadent) FDP or a ceramic-ceramic (ZirCAD and ZirPress, Ivoclar, Vivadent) FDP. Two implants (Osseospeed, Dentsply) and custom abutments (Atlantis, Dentsply) supported these FDPs, which were cemented with resin cement (RelyX Universal Cement). Baseline photographs were made with markings of teeth from maximum intercuspation (MI) and excursive function. Patients were recalled at 6 months and 1 to 3 years. Fractures were observed, their locations recorded, and images compared with baseline photographs of occlusal contacts.

Conclusion—No significant relationship exists between the occurrence of fracture and: (1) the magnitude of bite force; (2) a tooth distal to the most distal retainer; and (3) contacts in load-bearing or non-load-bearing areas. However, there was a significantly higher likelihood of fracture in areas with MI contacts only.

Clinical Significance—This clinical study demonstrates that there is a need to evaluate occlusion differently with implant-supported prostheses than with natural tooth supported

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prostheses because of the absence of a periodontal ligament. Implant supported prostheses should have minimal occlusion and lighter contacts than ones supported by natural dentition.

Keywords

fractography; ceramic-ceramic FDP; metal-ceramic FDP; occlusion; occlusal contact; failure analysis

Introduction

Ceramic-ceramic prostheses are becoming a preferred option for esthetic restorative dental procedures. They offer optimal esthetics compared with metal-ceramic prostheses as well as less tooth reduction, a supragingival finish, and faster turnaround time with computer-aided design and machining (CAD-CAM). However, ceramic-ceramic prostheses are more susceptible to fracture because of the lower fracture resistance of the veneering ceramics (1). Thus, proper treatment planning is necessary to determine the optimum design and placement location of these ceramic-ceramic prostheses. Yttria-stabilized tetragonal zirconia polycrystalline (Y-TZP) ceramics are the strongest and toughest core materials for ceramic FDPs (1). These materials exhibit the highest flexural strength and fracture toughness of all dental ceramics partially because of a phenomenon known as transformation toughening. The phenomenon known as transformation toughening occurs during a reverse tetragonal to monoclinic transformation. It is considered beneficial in that the material can actually “heal” itself. When tensile stresses are generated at the tip of a crack, the reverse tetragonal to monoclinic transformation occurs. This phase change at the tip of the crack is accompanied by volumetric expansion and subsequent compressive stresses around the crack tip. This volumetric expansion can result in partial closure of the crack and prevent its propagation through the entire structure (2). However, these core ceramics can undergo adverse localized phase transformations (3, 4), and *in vivo* chipping of their ceramic veneers is a relatively frequent occurrence (5). Low-temperature degradation (LTD) is a phenomenon in zirconia, which induces tetragonal to monoclinic transformation at the surface of the specimen in the presence of moisture at 250°C, causing tensile stresses on the surface.

Multiple unit FDPs have been shown to have more complications than single crowns alone (6). A systematic analysis (7) showed that the survival probability of FDPs after 10-year was 89.1% while the probability of success was only 71.1%. The 10-year risk for caries was 2.6% and periodontitis leading to FPD loss was 0.7%. The 10-year risk for loss of retention was 6.4%, for abutment fracture 2.1% and for material fractures was 3.2%. This probability analysis was further confirmed by Sailer et.al (8) where they found technical complications such as material fracture, loss of retention and biological complications like caries and loss of pulp vitality were similar to occur over 5 years for FDPs regardless of material used. However, the 5-year survival of metal-ceramic FDPs was significantly higher at 94.4% ($P<0.0001$) than the survival of all-ceramic FDPs, at 88.6%. The frequencies of material fractures (framework and veneering material) were significantly ($P<0.0001$) higher for ceramic-ceramic FDPs (6.5% and 13.6%) compared with those of metal-ceramic FDPs (1.6% and 2.9%). However, when zirconia was used as the framework material, failures were primarily attributed to other reasons such as biological and technical complications.

Dental implants are steadily becoming the treatment of choice for supporting metal-ceramic and ceramic-ceramic partial dentures. Meta-analysis studies show that the cumulative success rates for implant-supported FDPs are 95.2 % over a period of 5 years and 86.7% and over a period of 10 years (9). Conversely, conventional tooth-supported FDPs have survival levels of 93.8 % after 5 years and 89.2% after 10 years. Only 61.3% of the implant supported FDP patients did not have any complications after a period of 5 years compared with 84.3% of patients who had tooth supported FDPs. Failures for the tooth supported FDPs were attributed to biological complications such as secondary caries and loss of pulp vitality. Failures for the implant supported FDPs were attributed to technical complications, the most frequent being veneer fractures. Other technical complications include screw or abutment loosening and loosening of prosthesis (6). Peri-implantitis and soft tissue complications occurred in 8.6% of FDPs after 5 years (9). However, the studies reviewed in this analysis do not include ceramic-ceramic materials for the FDPs. Thus, there is a dearth of information on the performance and survival of implant-supported ceramic-ceramic prostheses.

A systematic review of clinical studies reveal that the cumulative survival rate over a 5-year observation period for ceramic-ceramic FDPs is 88.6% compared with 94.4% for metal-ceramic FDPs (10). Several ceramic-ceramic systems have been introduced to improve esthetics and survivability of all-ceramic restorations. The core ceramics for these prostheses include alumina, glass-infiltrated ceramic, lithium disilicate glass-ceramic, and zirconia (11–14). Zirconia substructures are the strongest and toughest of the ceramic dental frameworks (4, 15–17). A systematic analysis of zirconia-based tooth supported FDPs revealed a survival rate of 94.3% (18). However, when technical complications such as chipping of the veneer ceramic are included, their FDP survival decreases to 76.4% (18). Heinze and Rousson (1) performed a systematic review to analyze the prosthesis performance and reported three-year survival percentages of 90% for zirconia-supported FDPs and 97% for metal-supported FDPs. They concluded that veneer chipping was a major cause of failure. Long-term survival of zirconia frameworks over a period of 10 years has been reported to be as high as 91.5% (19), although some prostheses exhibited evidence of marginal deficiencies and veneer chipping. The objective of this research study was to test the following hypotheses:

1. There is no statistically significant difference in the fracture probability of the veneer ceramic of three-unit, posterior, implant-supported ceramic-ceramic FDPs that either have or do not have a tooth distal to the most distal retainer.
2. There is no statistically significant difference between the number of fractures located along load-bearing areas and the non-load-bearing areas (lingual cusps for mandibular teeth and buccal cusps for maxillary teeth) or along areas where there are excursive contacts and maximum intercuspation contacts.
3. There is no significant correlation between magnitude of bite force and the presence or absence of veneer ceramic fractures.

Materials and Methods

Study Design

This randomized, controlled, clinical trial was conducted to determine the performance and survival of implant-supported, three-unit fixed dental prostheses (FDPs) as a function of several design parameters. This single blind pilot study included a total of 68 participants, who required a total of 89 FDPs to replace missing posterior teeth. The participants' prosthesis sites were randomly designated to receive either a metal-ceramic or a ceramic-ceramic FDP. These sites were further subdivided according to the thickness of the veneer ceramic, the connector's radius of curvature, and the connector height. The overall thickness of the core ceramic plus veneer ceramic was 2.0 mm. Thus, the ratio of the veneer thickness to core thickness was variable. The veneer thickness ranged from 0.5 mm to 1.5 mm.

Prosthetic materials

Implants—Commercially pure titanium that was air-blasted with titanium dioxide and fluoride particles (Osseospeed, Astra Tech/Dentsply, Sweden)

Custom abutments—Gold-shaded, custom-milled, titanium abutments (Atlantis, Astra Tech/Dentsply, USA)

Metal ceramic FDP (MC)—A noble Pd-Au-Ag alloy (Capricorn, Ivoclar, Vivadent, Schaan, Liechtenstein) was veneered with a press-on leucite-reinforced glass-ceramic veneer (IPS InLine POM, Ivoclar Vivadent).

Ceramic-ceramic FDP (CC)—An yttria-stabilized zirconia core ceramic (IPS e.max ZirCAD, Ivoclar Vivadent, Schaan, Liechtenstein) was veneered with a pressable fluorapatite glass ceramic (IPS ZirPress, Ivoclar Vivadent, Schaan, Liechtenstein)

Study Population

Participants were recruited through broadcast e-mail, flyers, and newspaper advertisements. Participants were selected based on the following criteria:

- Ages between 21 and 75 years
- No contraindications to dental treatment
- Good overall dental health (no active caries, no periodontal disease, and periodontal pocket depth less than 4 mm)
- Missing at least three posterior teeth
- Natural teeth opposing the edentulous area and a full complement of teeth or restored teeth in all other areas of the mouth
- Adequate bone height and width in areas of proposed implants (no less than 6 mm of bone height for the shortest length of implant)
- Adequate interocclusal distance to accommodate the prosthesis (no less than 6 mm to account for abutment height, and height of prosthesis)

- Good oral hygiene and compliance with oral hygiene instructions as determined by the amount of plaque present on tooth surfaces
- Compliance with appointments and willingness to pay \$2625 for a 3-unit implant-supported FDP

Study Intervention

A total of 68 enrolled participants (29 male; 39 female) were randomly assigned to one of two groups, to receive either a metal-ceramic or a ceramic-ceramic FDP. No participant was selected to receive more than two posterior FDPs. Groups were further subdivided according to design parameters. A computer-generated random number table was formulated to facilitate assignment of each subject to a specific. Each participant was assigned a particular group of variables based on their enrollment time in the study. Participants were treated at the University of Florida College of Dentistry (UFCD) between 2008 and 2012. The UFCD Institutional Review Board approved the research protocol (IRB 95–2007) for treating human subjects. All subjects were required to sign an informed consent form prior to initiating the study, which was obtained by either the principal investigator or the study coordinator. The following baseline information was recorded:

- General medical history and physical examination data
- Maximum bite force (measured by a gnathodynamometer)

Participants were evaluated for bone height and bone width through computerized tomography. Some participants were treated by an oral surgeon if bone augmentation was required prior to placement of implants. Healing time was controlled by the extent of bone augmentation and typically ranged from four to six months. Two implants were placed using a surgical guide. Final impressions were made after eight weeks of healing using the open-tray technique. Final impressions were made with vinylpolysiloxane impression material (Aquasil, Dentsply Caulk). Type IV stone (Die-Keen, Whip Mix Corp) and soft tissue material (Gingitech, Ivoclar Vivadent, Schaan) were poured in the impressions. Mounted casts were prepared for abutment fabrication, allowing 2 mm interocclusal clearance for the FDP prosthesis. Custom abutments were prepared to allow for accurate representation of occlusion. For ceramic-ceramic FDPs, core substructures were milled from pre-sintered ceramic blanks after they were designed by a CAD system (InEOS, Sirona). For metal-ceramic FDPs, wax patterns for metal substructures were prepared, measured to exact dimensions, burned out, and the metal was cast into the mold cavity. Frameworks were designed to ensure proper support of the veneering ceramic and the framework substructures were inserted intra-orally along with the custom abutments to determine the accuracy of mounting. An occlusal record was confirmed using acrylic resin (Duralay resin, Reliance Dental Mfg. Co., Worth, IL). Corresponding veneer ceramics were applied and fired according to the manufacturers' instructions. Completed FDPs were seated and evaluated prior to cementation. Occlusal adjustments were made with an ultrafine-grit diamond bur (Brassler, USA). Occlusion was adjusted to ensure light contact with an 8- μ m-thick shim stock (Shimstock Occlusion Foil, Almore, USA). Adjusted FDPs were polished with abrasive wheels and diamond paste. FDPs were cemented with a resin cement (RelyX Unicem Self-Adhesive Universal Resin Cement, 3M ESPE). After cementation, occlusal

markings were recorded at maximum intercuspation (MI) (shown in red) and excursive movements (shown in black) (Figure 1). Both movements were marked using Accufilm (Parkell, USA) and photographed for baseline records. Vinylpolysiloxane impressions (VPS) were made of each quadrant as baseline records. Subsequently, these occlusal markings were labeled in a sextant diagram (Figure 2) for subsequent statistical analysis. The first number of the double digit refers to the location of the tooth in the mouth. Numbers 1–3 designate maxillary tooth crowns with 1 being on the most mesial crown and 3 being the most distal crown. Numbers 4–6 designate mandibular crowns with 4 as the most mesial crown and 6 as the most distal crown. Each tooth was then divided into 6 areas and labeled 1–6 by proceeding in a clockwise order starting from the mesiobuccal part of the arrangement.

Post cementation Analysis

Participants were recalled at six months and annually for the three years after cementation. Participants were asked to report any unusual occurrence related to their prosthesis. Participants were immediately recalled before the designated recall time if they reported an actual or suspected fracture. VPS impressions were made of each quadrant at each recall visit and photograph images were recorded of occlusal markings. If a fracture was noted clinically, FDP surfaces were cleaned with a water spray, rinsed with ethanol, and air-dried. This procedure was repeated twice. A VPS impression of each fracture surface was made twice to fabricate acrylic replicates for fractographic analysis. Replicates of the fractured FDP surfaces were examined by SEM to determine the origin of fracture and to calculate the stress at fracture. Fractures were examined clinically and details of the fracture were recorded (20).

Statistical Methods

Statistical analysis was performed using the R statistical software package (Vienna, Austria; V.2.15.0) to calculate means, standard deviations and frequencies and to perform univariate tests between the observations of prostheses with and without fractures. A Mann Whitney test was used to compare relationships between bite force and fracture or no fracture and Fisher's exact test was used to analyze the effect of the presence of a distal tooth on the incidence of fracture (21).

Results

The consort diagram shows the population of patients, who were recruited for the study (Figure 3). Of the 89 FDPs, 41 (46%) were ceramic-ceramic and 48 (53.9%) were metal-ceramic. Thirteen (15%) of the 89 cemented FDPs exhibited fractures, six (14.6%) of which were ceramic-ceramic and seven (15%) were metal ceramic. These fractures developed from 8 to 497 days after cementation. Analysis of fracture surfaces was performed by comparing the maximum intercuspation site (MI) or sites of excursive contacts at cementation on baseline photographs to the sites of each fracture surface. The MI point of contact was associated with a high probability of fracture ($p=0.004$), but having excursive contact ($p=0.545$) or both points of contact ($p = 1.0$) were not associated with a significant probability of fracture.

Of the 13 bridges that fractured, 4 of them (31%) fractured at a point of MI contact. The rate of fracture at an MI contact point for FDPs with MI contact only was 12%.

Of the 13 FDPs that fractured, 3 of these prostheses (23%) fractured at a point of excursive contact. The rate of fracture at an excursive contact area for FDPs with any excursive contact occurred at a rate of 6%.

Of the 13 FDPs that fractured, 3 FDPs (23%) fractured at an area of both contacts. The rate of fracture for FDPs with both contact areas was 6%. Table 1 summarizes the distribution of the population with regards to the variables being examined and their statistical significance.

SEM analysis of fractured surface replicas revealed that all fractures originated from the occlusal surfaces of the restorations (Figs. 4 and 5). There was no statistically significant difference between the magnitude of bite force and the incidence of fracture ($p=0.804$). There was also no statistically significant difference between the presence or absence of a tooth distal to the distal retainer and the probability of fracture ($p=1.0$). There was no statistically significant difference between the presence of contacts on the non-supporting (non-loaded cusps) and fracture ($p=0.759$).

Discussion

Based on the results of this analysis, there was no evidence of an association between the magnitude of bite force and the incidence of fracture. This finding has been confirmed both for the incidence of fracture on natural teeth (22, 23) and wear of opposing enamel (24). Also, there was no evidence of an association between the presence or absence of a tooth distal to the distal retainer and the occurrence of fracture.

The hypothesis that a distal tooth will brace the ceramic crown anterior to it and this support would resist any oblique loading was proposed. However, because the fracture frequency was not significantly lower in these areas, this hypothesis was rejected. There is a possibility that a veneer ceramic that extends well beyond the load-support area of the core ceramic will be more susceptible to fracture. Using FDPs with a wide range of crown designs, veneer ceramic/core ceramic thickness ratios and methods of fabrication can test such a hypothesis. An *in vitro* study determined the effect of veneer fabrication on the strength of the veneer ceramics. The authors concluded that CAD-CAM manufactured veneers demonstrated higher fracture susceptibility because of the higher fracture strength than conventionally manufactured ceramic veneers (25). Another study examined the effect of multiple firings on veneer ceramics and found that multiple firings resulted in an increased density and decreased porosity, which accounted for increased fracture resistance (26).

This study is unique because it captured the areas of contact on the prosthesis immediately after cementation and allowed the investigators to characterize the occurrence of fracture along these contact areas. The results show that the presence of excursive contacts with or without maximum intercuspation contacts does not influence the occurrence of fracture. However, the presence of only maximum intercuspation contacts is highly significant for the occurrence of fracture. This is consistent with a study by Zhang et. al. (27) which explains the effect of mechanical degradation on the failure of ceramic restorations. This article

explains the role of mechanical fatigue on surfaces subjected to point contact, which results in crack propagation and eventually progresses to failure. This could be a rationale for why maximum intercuspation contacts proved to be more significant than excursive contacts in the occurrence of veneer fracture. This article further emphasizes the difference in the fracture location between veneered ceramic prostheses and monolithic ceramic prostheses. Veneered ceramic prosthesis have fractures originating from the occlusal surface as a result of the weaker glass-ceramic veneer being susceptible to surface cracking. Monolithic ceramic prostheses on the other hand exhibit fractures along the margin areas. Other studies (28, 29) have shown that contacts during maximum intercuspation in a normal dentition exhibit equal bilateral tooth contact areas between the left and right sides of the mouth. Also, the first molar site is the center of load, and it withstands the greatest amount of occlusal force, with this magnitude falling between those of the anterior and posterior teeth. This can possibly explain why these fractures have occurred in prostheses with maximum intercuspation contacts. These prostheses are supported by implants, which are firmly osseointegrated into bone. In contrast, natural teeth are supported by the periodontal ligament (30), which consists of fibers attached to bone. The periodontal ligament offers a cushion where natural teeth can deflect during chewing hard objects or during clenching (31, 32). This may explain these types of fractures since the natural teeth can deflect significantly during clenching or excessive mastication forces, whereas the implant-supported teeth cannot. An *in vitro* study determined the fracture resistance of ceramic-ceramic prostheses on natural abutment teeth and on implants (33). The investigators concluded that implant-supported ceramic prostheses fractured at higher loads than those supported by natural teeth because of the lack of a periodontal ligament. Despite the clearance that was provided for minimizing occlusal contacts (light passage of an 8- μ m thick shim stock foil), there does not seem to be any reduction in the magnitude of the masticatory forces. In another clinical study of zirconia based restorations examined over a period of nine years, the authors concluded that the use of implants as support ($p=0.026$) for these restorations was a risk factor associated with higher veneer failure rates along with the absence of an occlusal nightguard ($p=0.0048$), the presence of a ceramic restoration as an antagonist ($p=0.013$), and the presence of parafunctional activity ($p=0.018$) (34).

Conclusion

This study demonstrated that there was a significant correlation between the presence of maximum intercuspation contacts and the occurrence of fracture. There was no evidence to reject the hypotheses that there was no correlation between the fractures and (1) the magnitude of the bite force; (2) the presence or absence of a distal retainer; (3) and the location within the supporting and non-supporting areas of the teeth. The authors theorize that the correlation between MI contacts and fracture is a result of the resistance to deflection of implant-supported prostheses.

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Figure 1.
Ceramic-ceramic FDP showing occlusal markings at cementation.

Figure 2. Sextant numbering system for statistical analysis of occlusal contacts on teeth. This illustrates the same maxillary bridge on Figure 1 overlaid with sextant markings.

Figure 3.
CONSORT diagram detailing the recruitment and retention of patients.

Figure 4.
Same FDP in Fig 2 fractured after 298 days in service showing fractured veneer on the mesiolingual.

Figure 5.
SEM analysis of fracture indicates origin on the occlusal surface with numerous arrest lines emanating from the area.

Table 1

Variables which were examined with the study population regarding fracture and their statistical significance.

	Overall (n=89)	No fracture (n=76, 85.4%)	Fracture (n=13, 14.6%)	p-value†
Type				
All ceramic	41 (46.1%)	35 (85.4%)	6 (14.6%)	1*
PFM	48 (53.9%)	41 (85.4%)	7 (14.6%)	
Veneer				
0.5	37 (41.6%)	31 (83.8%)	6 (16.2%)	.955**
1	21 (23.6%)	19 (90.5%)	2 (9.5%)	
1.5	31 (34.8%)	26 (83.9%)	5 (16.1%)	
Diameter				
0.5	39(43.8%)	33 (84.6%)	6 (15.4%)	.654**
1	22 (24.7%)	18 (81.8%)	4(18.2%)	
1.5	28 (31.5%)	25 (89.3%)	3 (10.7%)	
Connector				
3	25 (28.4%)	22 (88.0%)	3 (12.0%)	.959**
4	32 (36.4%)	27 (84.4%)	5 (15.6%)	
5	31 (35.2%)	27 (87.1%)	4 (12.9%)	
MI contact				
No	55 (61.8%)	52 (94.5%)	3 (5.5%)	.004*
Yes	34 (38.2%)	24 (70.6%)	10 (29.4%)	
Non-supporting cusp contact				
No	34 (38.2%)	30 (88.2%)	4 (11.8%)	.759
Yes	55 (61.8%)	46 (83.6%)	9 (16.4%)	
Excursive contact				
No	37 (41.6%)	31 (81.6%)	6 (16.2%)	.767*
Yes	52 (58.4%)	45 (86.5%)	7 (13.5%)	
Both contact				
No	35 (39.3%)	30 (85.7%)	5 (14.3%)	1*
Yes	54 (60.7%)	46 (85.2%)	8 (14.8%)	
Any contact				
No	6 (6.7%)	6 (100%)	0 (0%)	.587*
Yes	83 (93.3%)	70 (84.3%)	13 (15.7%)	
Bridge location				
Lower	58 (65.2%)	49 (84.5%)	9 (15.5%)	1*
Upper	31 (34.8%)	27 (87.1%)	4 (12.9%)	