A Photoelastic Stress Analysis of Screw- and Cement-Retained Implant Prostheses with Marginal Gaps

Jae-In Lee, DDS, PhD;* Yoon Lee, DDS, PhD;† Nan-Young Kim, DDS, PhD;‡ Yu-Lee Kim, DDS, PhD;§ Hye-Won Cho, DDS, PhD¶

ABSTRACT

Background: The precise fit of an implant prosthesis is considered to be a prerequisite for the success and maintenance of osseointegration. It is unknown how much static stress can be tolerated at the implant-bone interface with ill-fitting prostheses for the two different types of retention (cement vs screw).

Purpose: The purpose of this study was to evaluate the stress pattern and magnitude in the supporting tissues around ITI (Straumann AG, Waldenburg, Switzerland) implants with screw- or cement-retained prostheses with marginal gaps by photoelastic analysis.

Materials and Methods: A photoelastic model of a human mandible, partially edentulous distal to the canine, was made of PL-2 resin. Three ITI implants (4.1 × 10 mm, Straumann AG, Waldenburg, Switzerland) were placed in the posterior edentulous region, and screw- or cement-retained three-unit fixed partial dentures (FPDs) were fabricated. Ill-fitting prostheses were made by placing a 100-µm gap between the abutments and the superstructures on the second premolar or the first molar. A static vertical force of 134 N was applied at three loading points on each prosthesis. Photoelastic stress analysis was carried out to measure the fringe order around the implant-supporting structures.

Results: Even in the unloaded condition, low-level stresses were generated around the implants after screw tightening or cementing the three-unit FPDs with marginal gaps. Loading on the terminal implants developed high concentrated stresses around the loaded implant, regardless of the types of restorations or the presence of gaps. However, when the middle implant was loaded, moderate stresses were distributed to the anterior and posterior implants.

Conclusions: Screw-retained FPDs with gaps exhibited a wider range of stresses on the interproximal region of adjacent implants than cement-retained FPDs. However, severe misfit in the prosthesis caused the nonaxial stress transfer to the adjacent implants in the cement-retained FPDs with gaps.

KEY WORDS: cement-retained FPD, dental implant, gap prosthesis, photoelasticity, screw-retained FPD

INTRODUCTION

Implant dentistry has advanced remarkably since the concept of osseointegration was first applied clinically to restore missing teeth.[1] The implant design, bone quality and quantity, surgical procedure, fit of the prosthesis, proper occlusion, regular postoperative checkups, and the patient's oral hygiene are important for the long-term success of implants. Among these factors, many studies have emphasized the importance of the fit of the superstructure, and it has been suggested that the occlusal force on the prosthesis needs to be properly distributed to maintain osseointegration.[1,2] If tensile, compressive, and bending stresses remain due to an

*Assistant professor, Department of Prosthodontics, College of Dentistry, Wonkwang University, Iksan, Korea; †assistant professor, Department of Dentistry, Wonju College of Medicine, Yonsei University, Wonju, Korea; ‡private practice, former graduate student, College of Dentistry, Wonkwang University, Iksan, Korea; §associate professor, Department of Prosthodontics, College of Dentistry, Wonkwang University, Iksan, Korea; ¶professor, Department of Prosthodontics, College of Dentistry, Wonkwang University, Iksan, Korea

Reprint requests: Professor Hye-Won Cho, Department of Prosthodontics, College of Dentistry, Wonkwang University, 344-2 Shinyong-dong, Iksan, Jeonbuk 570-749, Korea; e-mail: hwcho@wku.ac.kr

DOI 10.1111/cid.12134

ill-fitting superstructure, various problems may arise such as screw loosening and failure of osseointegration.[2–4] Millington and Leung[5] reported that a discrepancy greater than 6 μm at the implant-prosthesis interface can induce stresses on the superstructure. Moreover, if the implant-supported prostheses do not fit passively, the stresses are superimposed on those produced by functional loads, which may cause pain and discomfort in the short term and contribute to screw loosening, fracture, or failure of osseointegration. Therefore, implant-retained prostheses need to be fabricated with precision. Many methods may be used to improve the fit of the prostheses connected to multiple implants. However, even though the fit of the prosthesis may be improved with the use of several techniques (sectioning and soldering, magnification, radiographic evaluation, one-screw tests, modified impression techniques, the verification index, spark erosion, and laser welding), it is still very difficult to fabricate a completely precise prosthesis.[6] Jemt[7] found that there were vertical distortions of 9 to 296 μm in implant-supported prostheses. Jemt and Book[8] reported that on average, a gap of 100 μm was present in fixed prostheses of the fully edentulous maxilla. However, they concluded that there was not any definite correlation between the misfit of the prosthesis and cervical bone loss, and the bone exhibited biologic tolerance. Alternatively, Kunavisarut and colleagues[9] reported that when a 111-μm gap was placed between the abutment and the implant, the stress on the implant-supporting tissue increased by 8 to 64%.

Certain clinicians have claimed that it is very difficult to achieve passive fit in screw-retained implant prostheses and have suggested that cement-retained prostheses should be used as in conventional fixed prosthesis to compensate for the inaccuracy of the superstructure.[10,11] Guichet and colleagues[12] compared the fit of screw-retained and cement-retained prostheses and found that the fit improved after screw tightening, whereas cement-retained prosthess showed better stress distribution. However, Heckmann and colleagues[13] emphasized the importance of the fit of the prosthesis given that not only screw-retained prostheses but also cement-retained prostheses showed significant stress in the implant-supporting bone during screw tightening or cementation. Currently, the maximum clinical tolerance of the misfit of the implant prosthesis has not been verified. It is unknown how much static force the implant-bone interface may withstand. It is also unknown whether passive fit is an essential prerequisite for maintaining long-term osseointegration. In addition, the correlation between fit accuracy and the stress distribution in cement-retained and screw-retained implant prostheses is unclear. Therefore, the purpose of this study was to evaluate the stress distribution pattern and magnitude in the supporting tissues around ITI implants in the mandibular posterior region with ill-fitting screw- or cement-retained prostheses using photoelastic analysis.

MATERIALS AND METHODS

Construction of the Photoelastic Model

To make a photoelastic model, a partially dentate mandibular model, which was edentulous distal to the canine, was duplicated, and a master stone model was fabricated. At the adjacent canine, a socket was prepared on the root, and three ITI solid screw implants (4.1 mm in diameter and 10 mm in length, Straumann AG, Waldenburg, Switzerland) were installed vertically using a surveyor at the positions of the first premolar (#1), second premolar (#2), and the first molar (#3) so that the implants were 4 mm apart and 2 mm away from natural teeth. Impression caps (synOcta®, Straumann AG) were connected to the installed implants so that the neck area with the machined smooth surface was exposed above the model and fixated with inlay wax. A mold was fabricated using silicone rubber (KE1300, Shin-Etsu, Tokyo, Japan), and impression caps and the implants were repositioned on the silicone mold to represent complete integration. On the silicone mold, photoelastic resin (PL-2, Vishay Micro-Measurements, Raleigh, NC, USA) with an elastic modulus similar to the cancellous bone was injected and polymerized at room temperature. At the same time, a silicone mold of the adjacent canine was fabricated, and photoelastic resin (PLM-1, Measurements Group, Raleigh, NC, USA) similar to the teeth was injected and bonded to the socket of the photoelastic model (Figure 1).

Fabrication of Screw- and Cement-Retained 3-Unit Fixed Partial Dentures

Impression caps were connected to the implants, and an impression was taken using an individual tray and silicone impression material (Honigum® Mono, DMG, Hamburg, Germany). Analogues were connected to the impression copings, and silicone (Gi Mask, Coltène/Whaledent AG, Altstätten, Switzerland) was added to

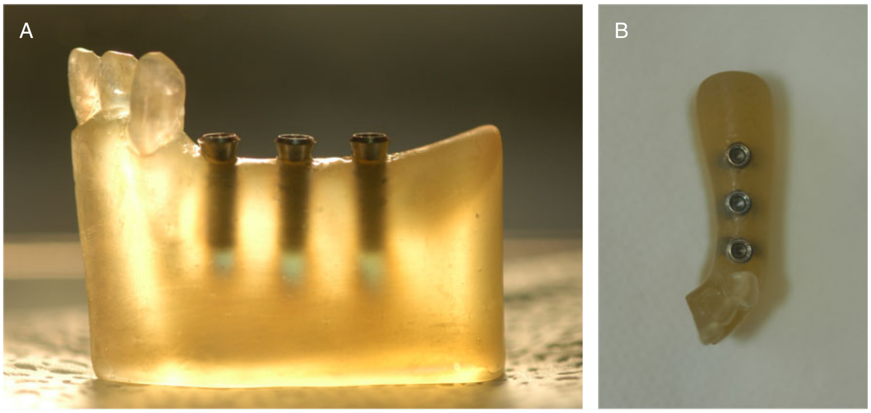

Figure 1 Photoelastic model with three implants placed in the mandibular posterior region. *A*, Buccal view; *B*, occlusal view.

reproduce the surrounding soft tissue. On the impression, vacuum-mixed die stone (Implant Die Stone, Talladium Inc., Santa Clarita, CA, USA) was used to fabricate a working model. On the model, a screw-retained three-unit fixed partial denture (FPD) was fabricated.

For the fabrication of the screw-retained prosthesis, synOcta abutments (Straumann AG) 2.5 mm in height were connected to the analogues on the working models (Figure 2A). Subsequently, synOcta gold copings for bridge (Straumann AG) were connected on the abutments with SCS Occlusal screws (Straumann AG) and splinted with pattern resin (Pattern resin, GC Inc., Tokyo, Japan). The crowns were waxed up 8-mm high and premolar shaped, and the occlusal surfaces were milled flat with a milling machine (PF-200, CM., Biel-Bienne, Switzerland) to later set the loading points. Before investment, the wax pattern was positioned on the photoelastic model to determine the accuracy of the fit.

For the fabrication of the cement-retained prosthesis, 5.5-mm high solid abutments (Straumann AG) were connected on the three implants in the photoelastic model using 35-Ncm torque (Figure 2B). An impression was taken with impression caps and positioning cylinders (Straumann AG) using an individual tray and silicone impression material and poured with die stone to fabricate a working model. The plastic copings for bridge (Straumann AG) were connected on the analogues and splinted with pattern resin. The wax patterns were fabricated with the same method as for the screw-retained prostheses.

After investment and burnout, the prostheses were cast with type III gold alloy (Cast-2, Alphadent, Seoul, Korea). The FPDs were sandblasted and acid treated. Under a laboratory microscope with ×10 magnification, the internal surface of the casting body was examined, and using a silicone material (Fit-Checker, GC Inc.) and reamer, the cervical margin was adjusted until the

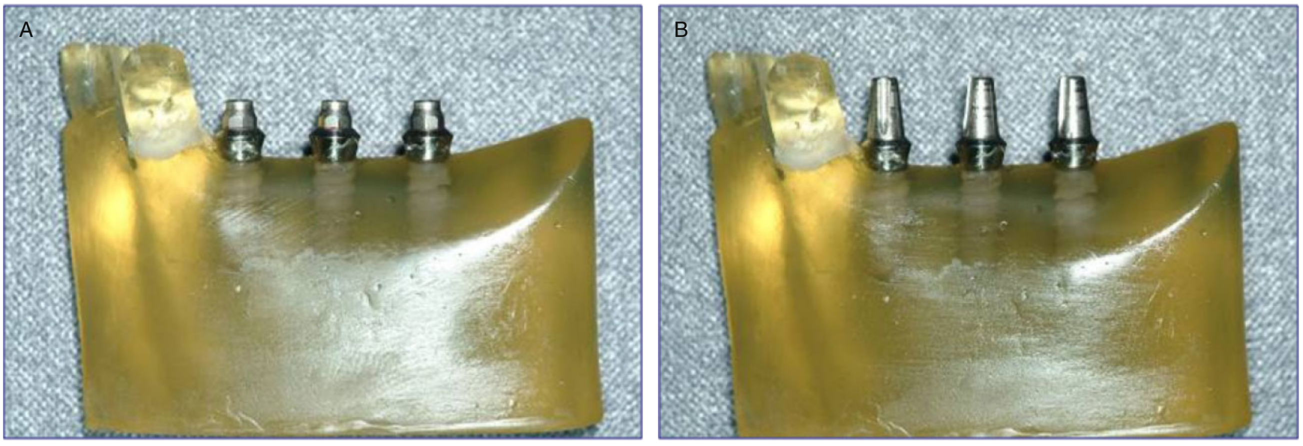

Figure 2 Abutments connected on three implants. *A*, synOcta abutments for screw-retained fixed partial denture (FPD). *B*, Solid abutments for cement-retained FPD.

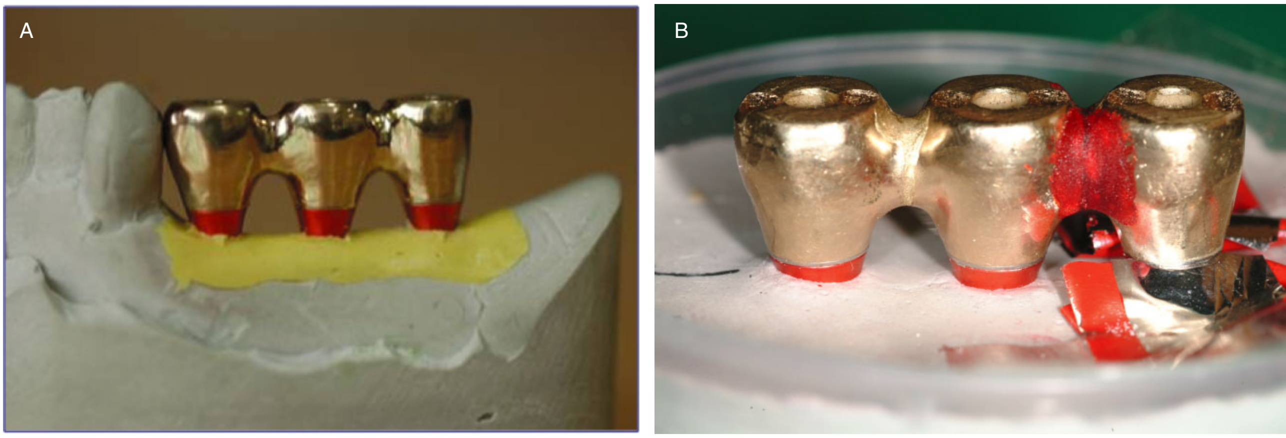

Figure 3 Completed screw-retained fixed partial denture (FPD). *A*, FPD without a gap on the master cast. *B*, Gap produced on the #3 implant using articulating papers.

three-unit FPDs showed a precise fit (Figure 3A). If there was an excessive stress, the casting body was cut and reattached by soldering.

In the screw-retained FPD, synOcta abutments were connected on the implants with a 35-Ncm torque starting from the most mesial implant. The prostheses were tightened with occlusal screws in the order of the #2, the #1, and then the #3 with a 15-Ncm torque.[14] In cement-retained FPD, solid abutments were installed with a 35-Ncm torque, starting from the most mesial implant, and then the prostheses were cemented with ZOE temporary cement (Cavitec, Kerr Co., Romulus, MI, USA) under 1 minute of 4.5 kg loading.

Gap Placement

After photoelastic stress analysis of the well-fitting prostheses, each crown was cut, and a 100-µm gap was placed. The placement of a 100-µm gap was based on the study by Jemt and Book,[8] which reported the average gap of a screw-retained implant prosthesis to be 100 µm.

Three types of marginal gaps were simulated:

- 100-µm gap at the #2 (#2 gap);
- 100-µm gap at the #3 (#3 gap);
- 100-µm gaps on both the #2 and #3 (#2, 3 gaps).

To place a 100-µm gap, a verification index was fabricated, and after each abutment was connected, 40-µm and 60-µm thick articulating papers (Bausch, Köln, Germany) were placed on the buccal and lingual surfaces of the abutment, respectively, inside the prosthesis (Figure 3B); the proximal surfaces were connected with resin (Pi-ku-Plast HP 36, Bredent, Senden, Germany). After 15 minutes of polymerization, the crowns were removed, and investment models for soldering were fabricated. The investment model was heated in a dental furnace, and gold was heated with a torch to solder the proximal surfaces. On the photoelastic model, the accuracy was determined under a microscope with ×10 magnification.

Photoelastic Stress Analysis

On the occlusal surfaces of the FPDs, three loading points were determined, and 1-µm deep loading points were formed with a #4 round bur. The loading points (P1–P3) were located at the center of the occlusal surface in the cement-retained prostheses and at the access holes in the screw-retained prostheses (Figure 4).

Prior to the experiments, the photoelastic model was inspected in the field of a circular polariscope

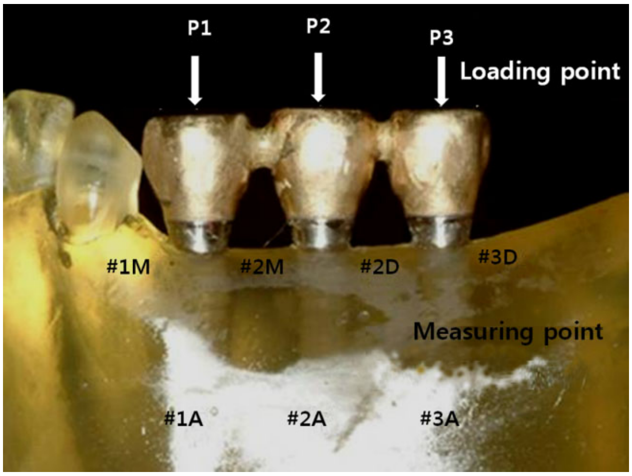

Figure 4 Three loading points (P1–P3) and seven measuring points (#1 M–#3 D).

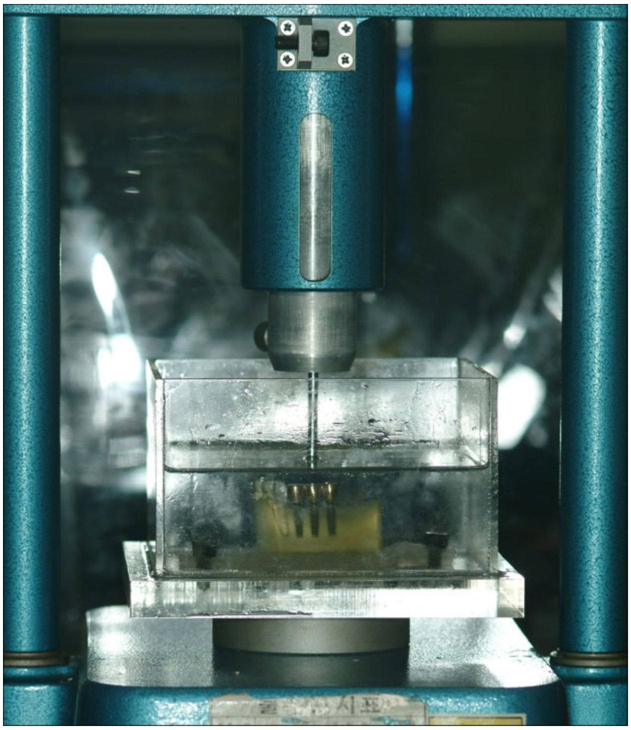

Figure 5 Loading device and photoelastic model mounted in a tank of mineral oil.

(Micro-Measurements) to ensure that the model was stress free. To minimize surface refraction, the photoelastic model was positioned in a transparent plastic tank filled with mineral oil using a jig.

A static vertical force of 134 N was applied at three loading points on each prosthesis (Figure 5). After each loading, there was a 5-minute resting period for the residual stress to disappear. In each group with a marginal gap, the stress on implant-supporting tissues was recorded.

The stresses after FPD connection and during loading were recorded with a digital camera (D100, Nikon, Tokyo, Japan).[15] At three measuring points on each implant surrounding tissue, seven measuring points in total (Figure 4), the fringe order (FO) was measured with reference to the isochromatic fringe characteristics shown in Table 1.

RESULTS

In a mandible with a posterior edentulous region, three implants were installed and restored with screw- or cement-retained three-unit FPDs. Three types of gaps were artificially created between the abutments and the FPDs, and the FO around the implant-supporting tissue was observed using photoelastic stress analysis; the results are represented in charts in Figures 6–23.

Under nonloaded conditions, the photoelastic resin cast was free of residual stress. Figures 6 and 7 indicate that a torque of 15 Ncm applied to the occlusal screws in screw-retained FPDs and the cement setting in cement-retained FPDs led to internal stress in the models. When screw-retained FPD without any gap was connected, minute stress (1.63 FO) was seen at the mesial crest of the #2 implant, whereas when implants were restored with cement-retained FPD without any gap, there was little stress in the supporting tissues. However, when there were gaps, minute interproximal stress (1.39 FO) was observed at the coronal parts between the implants in screw-retained FPDs. In the screw-retained #2 gap FPD, after screw-tightening, stresses of 1.39 FO developed in the mesial crest of the #1 implant and mesial and distal crest of the #2 implant. In the #3 gap FPD, stresses of 1.39 FO developed at the mesial crest of the #1 implant and mesial and distal crests of the #2 implant, whereas stresses of 1.08 FO developed in the apices of the #2 and the #3 implants. When there were gaps in the cement-retained FPDs, low-level stress (1.08 FO) occurred at the apices of the #2 and #3 implants in the #2 gap FPD, and coronal stress (1.39 FO) additionally developed in the #3 gap FPD under nonloaded conditions.

The isochromatic fringe patterns of the implants in the three loading conditions are presented in Figures 8–15. Stresses around the loaded implants under loading conditions P1 and P3 were compressive in nature, whereas the stress was not well dispersed to adjacent implants (Figures 18, 19, 22, 23). For all cases, high-level

TABLE 1 Isochromatic Fringe Characteristics

Color	Fringe Order
Black	0
Pale yellow	0.60
Dull red	0.90
Red/blue transition	1.00
Blue-green	1.22
Yellow	1.39
Rose red	1.82
Red/green transition	2.00
Green	2.35
Yellow	2.50
Red	2.65
Red/green transition	3.00
Green	3.10

Figure 6 Stresses produced by connecting the screw-retained fixed partial denture (FPD) without load. *A*, FPD without gaps. *B*, FPD with a 100-µm gap on the #2 implant. *C*, FPD with a 100-µm gap on the #3 implant. *D*, FPD with a 100-µm gap on the #2 and #3 implants.

stresses (2.35 FO) were observed around the apical regions of the loaded implants, especially in the cement-retained #2, 3 gap FPD, which exhibited the highest stresses (2.5 FO).

Under 134-N loading on the #1 implant, higher stresses were observed with the #2 gap FPD than the #3 gap FPD for both types. In screw-retained FPDs, the stress increased at the distal crest of the #1 implant (2.35 FO), whereas in cement-retained FPDs, the stress increased at the mesial crest of the #1 implant (2.35 FO). However, upon loading on the #3 implant, higher stresses were observed with the #3 gap FPDs than with the #2 gap FPDs in both types.

Generally, both types of prostheses developed similar stress patterns, except for the prostheses with #2, 3 gaps. In screw-retained FPD with #2, 3 gaps, the mesial stress (2.5 FO) increased on the #3 implant. In cement-retained FPD, apical stresses increased at the apices of all three of the implants.

Loading on the #2 implant revealed nearly equal load partitioning between the #1 and #3 implants for all cases. In the no-gap prostheses, stresses (1.39–1.63 FO) were observed around the #1 and the #3 implants, whereas there was little stress at the apex of the #2 implant in both types. When the #2 implant was loaded with screw-retained no-gap FPD, mesial and distal crestal stresses developed around the #2 implant (mesial 2 FO, distal 1.39 FO). In the cement-retained no-gap FPD, mesial and distal crestal stresses (1.39 FO) also developed, but the apical stresses at the #1 and the #3 implants were somewhat higher in the cement-retained FPD (1.63 FO) than the screw-retained FPD (1.39 FO).

Alternatively, in the cement-retained FPDs with #2 and #3 gaps, there were apical stresses present around

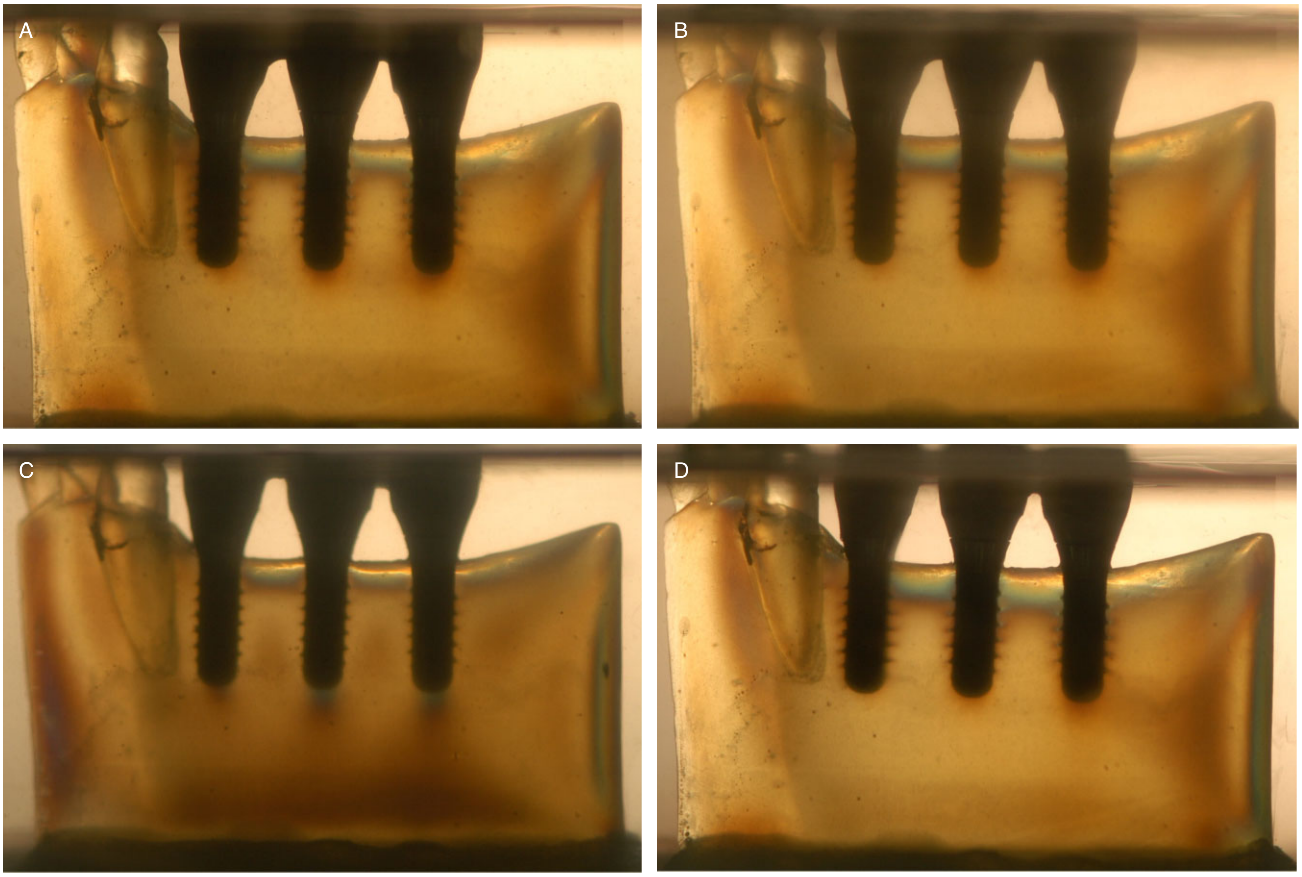

Figure 7 Stresses produced by cementing the cement-retained fixed partial denture (FPD) without load. *A*, FPD without gaps. *B*, FPD with a 100-μm gap on the #2 implant. *C*, FPD with a 100-μm gap on the #3 implant. *D*, FPD with a 100-μm gap on the #2 and #3 implants.

the #2 implant (1.22, 1 FO). In the cement-retained #2 gap FPD, the apical stresses in the #1 and the #3 implants slightly decreased compared with the no-gap FPD, and low-level stress (1.22 FO) at the #2 implant apex developed. In the screw-retained #2 gap FPD, the apical stresses in the #1 and the #3 implants slightly increased compared with the no-gap FPD, and the stress decreased at the mesial crest of the #2 implant and the distal crest of the #3 implant.

In the cement-retained #3 gap FPD, the stress at the mesial and distal crests of the #2 implant somewhat increased compared with the no-gap FPD, and the apical stress at the #1 implant decreased. In the screw-retained #3 gap FPD, the stresses at the mesial crest of the #2 implant and mesial and distal crest of the #3 implant decreased, whereas apical stress newly formed at the #2 implant. In both types of prostheses with #3 gap FPD, stress formed at the apex of the loaded #2 implant.

In both types of prostheses with #2, 3 gaps, stress increased compared with the one-gap prostheses. In screw-retained #2, 3 gap FPD, upon #1 implant loading, the stress patterns were similar to the #2 gap FPD, whereas the stress was higher in the mesial crest of the #1 implant compared with the #3 gap FPD. Upon #3 implant loading, the stress at mesial crest of the #3 implant in screw-retained #2, 3 gap FPD was higher than the #2 gap FPD and the #3 gap FPD. Upon #2 implant loading, the stress was higher in the mesial crest of the #2 implant and the mesial and distal crest of the #3 implant compared with the #2 gap FPD, whereas the apical stress of the #1 implant was lower. Compared with the #3 gap FPD, the stress increased at the mesial and distal crest of the #2 implant, thereby increasing the general coronal stress.

In the cement-retained #2, 3 gap FPD, upon #1 implant loading, the apical stresses of all three implants and the mesial crestal stress of the #1 implant were higher than the #2 gap FPD. Compared with the #3 gap FPD, the stresses at the apices of the #2 and the #3 implants were also high. Upon #3 implant loading, the

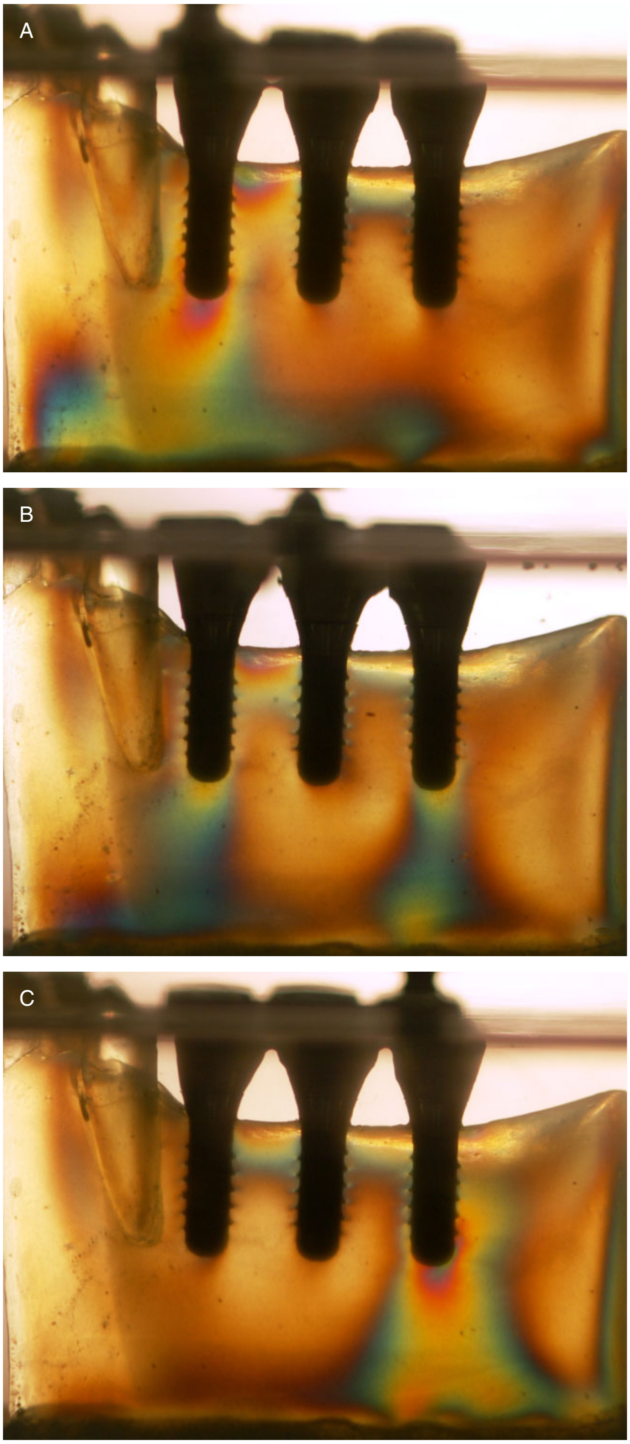

Figure 8 Stresses produced by the screw-retained fixed partial denture (FPD) without gaps under a 134-N load at P1, P2, and P3.

stresses at all three implant apices and the stresses at distal crest of the #2 and the #3 implants were higher than the #2 gap FPD. Compared with the #3 gap FPD, the stresses at all three implant apices and at the distal crest of the #3 implant were high, but the stress at the mesial crest of the #2 implant was low. Upon #2 implant loading, the apical stresses of all three implants and the distal crestal stress of the #3 implant were higher than the #2 gap FPD. Compared with the #3 gap FPD, the apical stresses of the #1 and the #2 implants and the

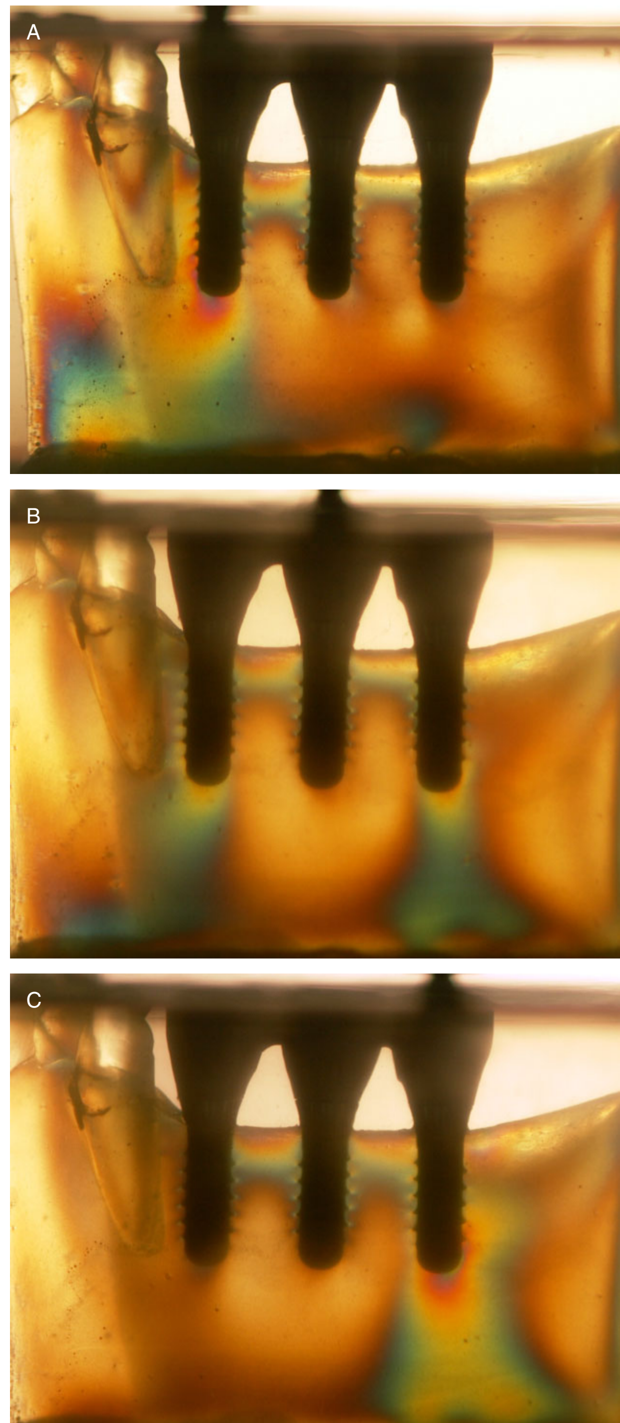

Figure 9 Stresses produced by the screw-retained fixed partial denture (FPD) with a 100-µm gap on the #2 implant under a 134-N load at P1, P2, and P3.

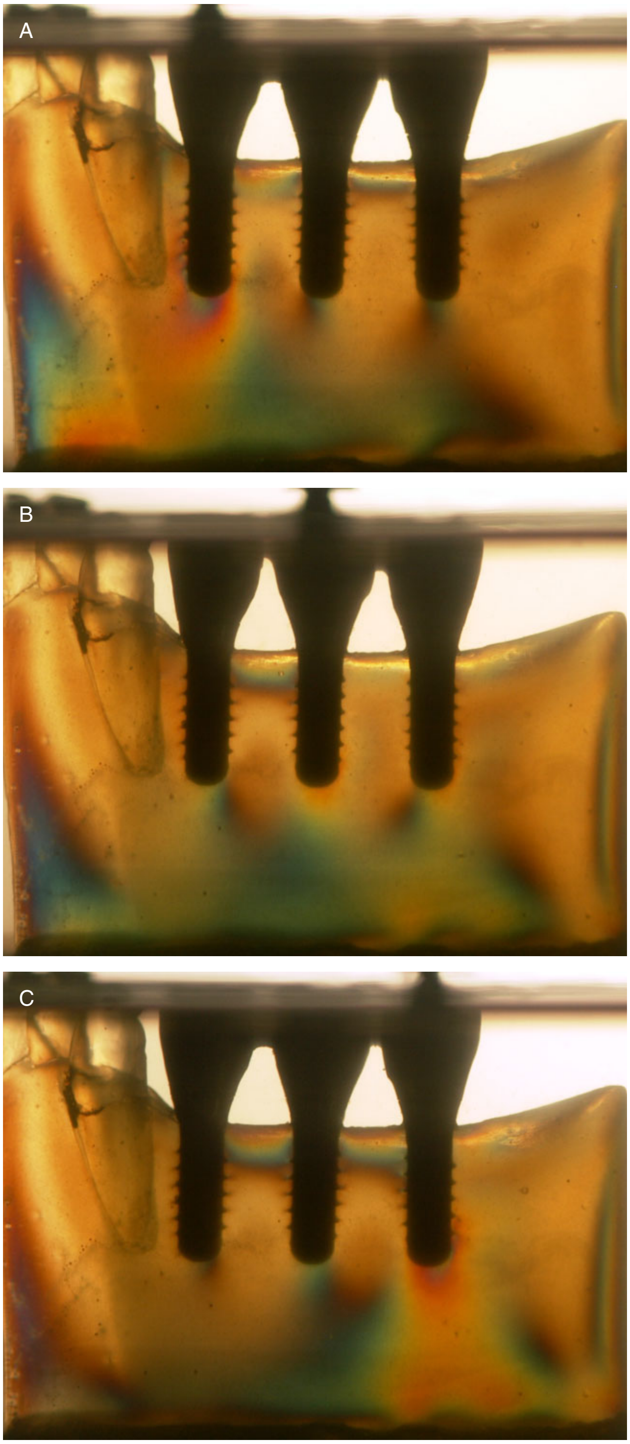

Figure 10 Stresses produced by the screw-retained fixed partial denture (FPD) with a 100-μm gap on the #3 implant under a 134-N load at P1, P2, and P3.

interproximal stresses around the #2 implant were high. In screw-retained prostheses, the coronal stresses increased, regardless of the position or the number of gaps, but in cement-retained prostheses, stress increased unstably on all of the implants.

DISCUSSION

It has generally been accepted that passive fit of an implant prosthesis is a prerequisite for the long-term success of dental implants.[13,14] However, distortion of the superstructure may occur during any step of its

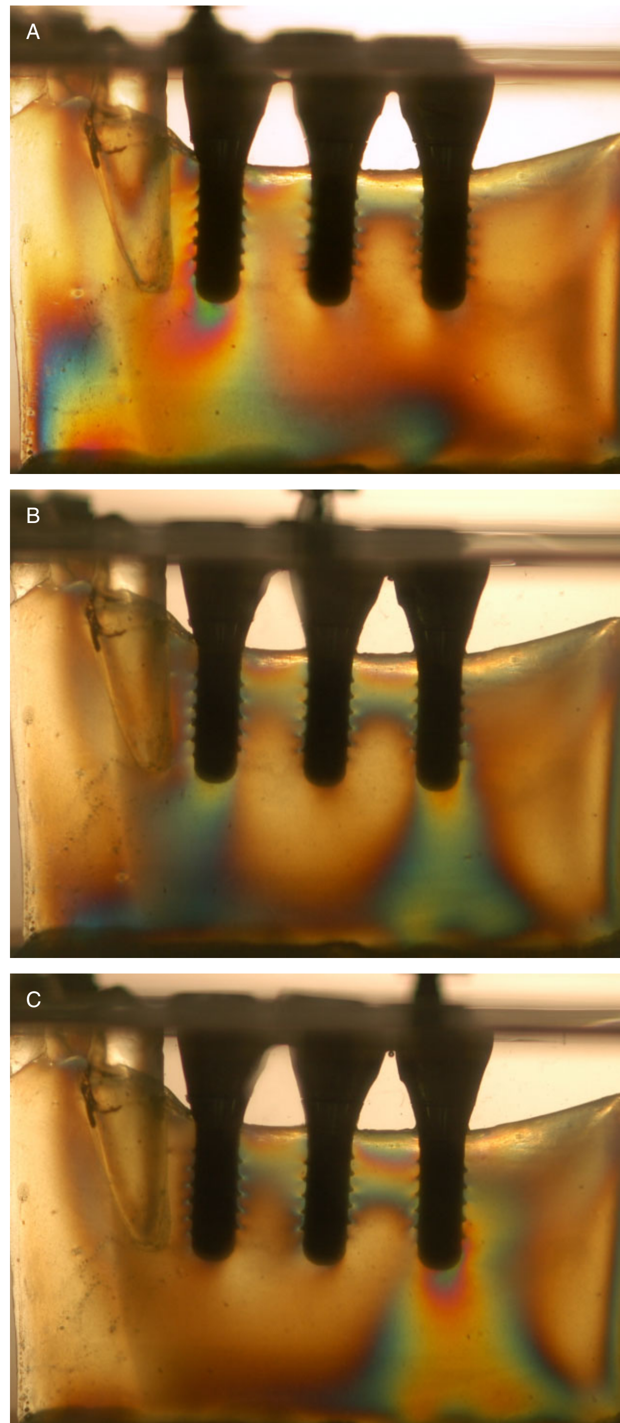

Figure 11 Stresses produced by the screw-retained fixed partial denture (FPD) with a 100-μm gap on the #2 and #3 implants under a 134-N load at P1, P2, and P3.

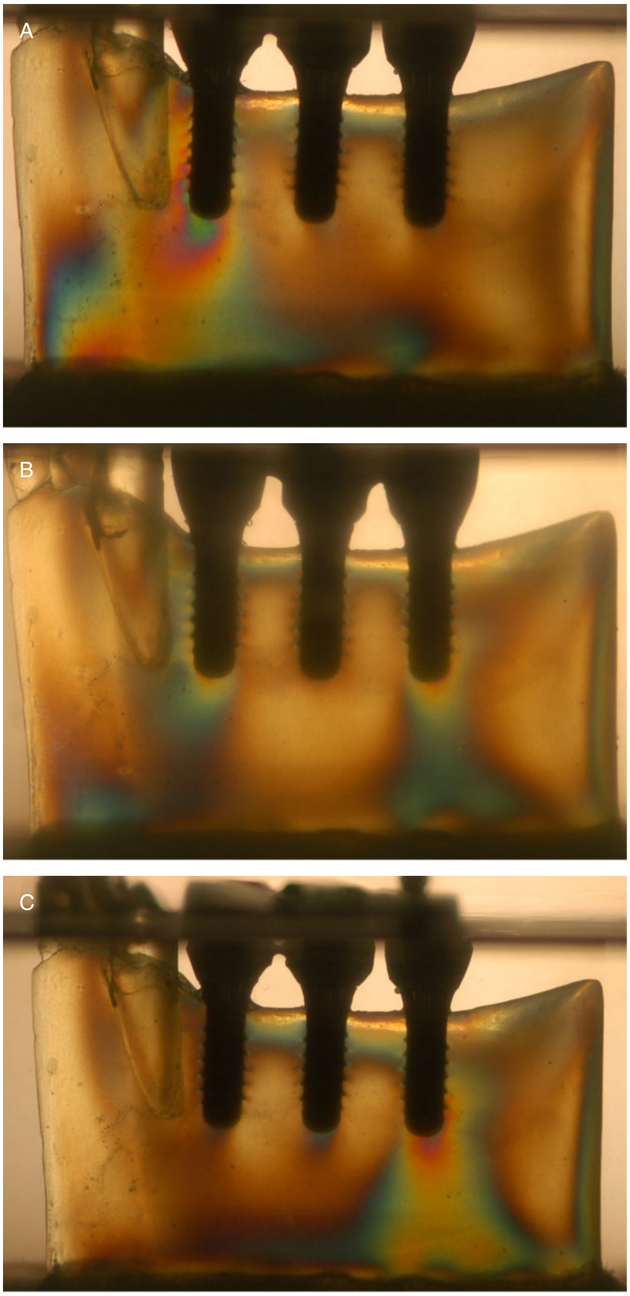

Figure 12 Stresses produced by the cement-retained fixed partial denture (FPD) without gaps under a 134-N load at P1, P2, and P3.

fabrication, such as impression taking, investment, casting, try in, and setting.[2,5] In addition, many studies have reported the presence of various gaps between the prosthesis and the implant.[5–9] Such misfit of prostheses may induce stress within the prosthesis, its components, or the supporting tissues,[5,9] negatively impacting the long-term stability of the implant; however, evidence supporting this concept is insufficient.

Misch[10] suggested that it is easier to achieve passive fit in cement-retained prostheses given that the gaps can be filled by the cement inside the prostheses, helping to distribute the loading at the bone-implant interface. Guichet and colleagues[12] reported that marginal gap decreased from 46.7 (± 29.8) to 16.5 (± 8.1) μm in screw-retained prostheses after screw tightening, but it caused stress in the implant components and the supporting tissues. However, in cement-retained prostheses, the marginal gap increased from 45.0 (± 29.1) to 49.1 (± 26.3) μm, and the achievement of passive fit was

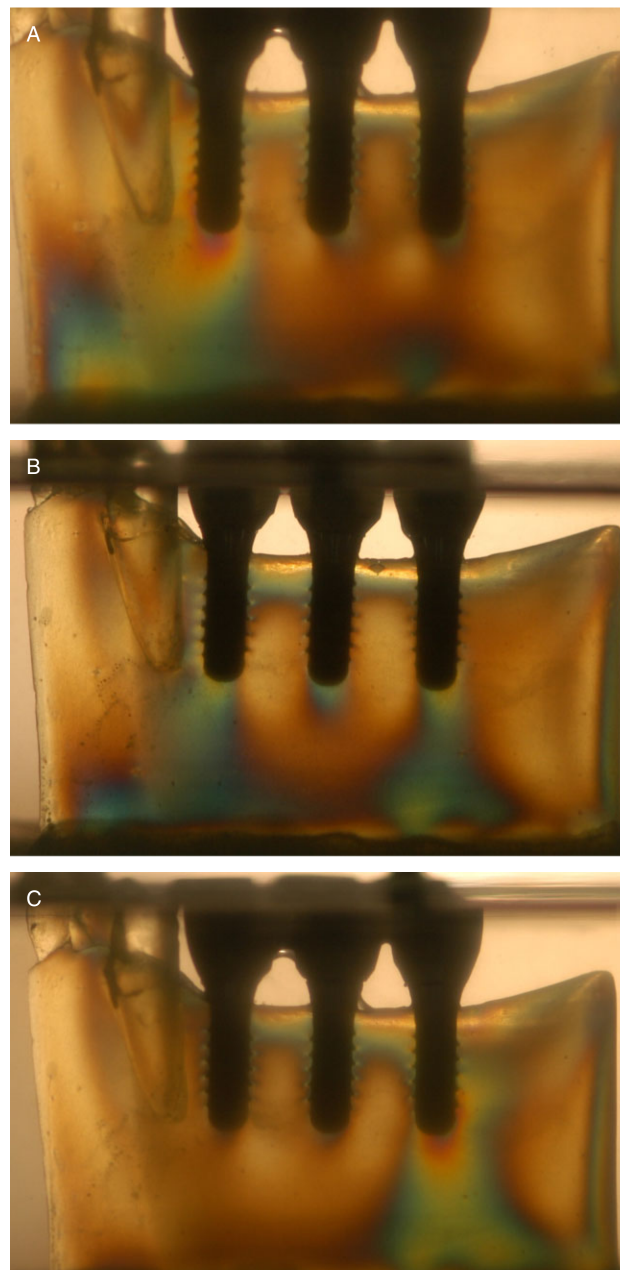

Figure 13 Stresses produced by the cement-retained fixed partial denture (FPD) with a 100-μm gap on the #2 implant under a 134-N load at P1, P2, and P3.

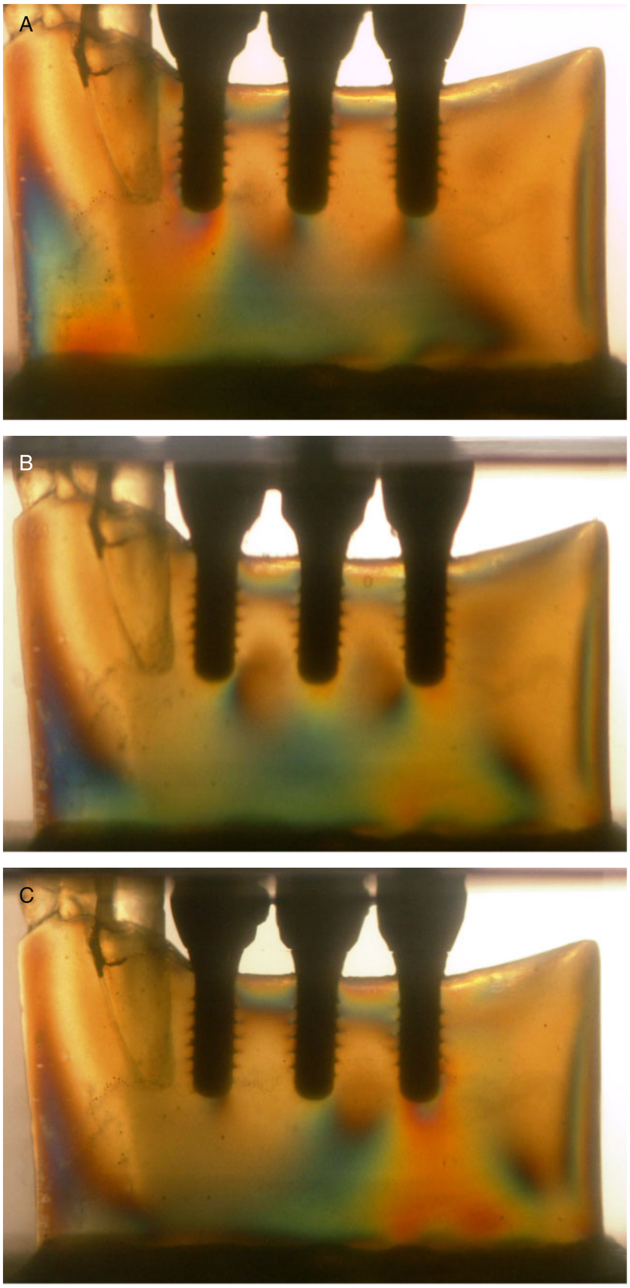

Figure 14 Stresses produced by the cement-retained fixed partial denture (FPD) with a 100-µm gap on the #3 implant under a 134-N load at P1, P2, and P3.

more likely due to the presence of more equitable stress distribution than in screw-retained prostheses. When both types of implant prostheses were connected, the photoelastic stresses in the supporting tissues were 0.5 to 1.5 FO at the apex or the cervical area, and when the prostheses were compared, in 80% of the prostheses, the cement-retained prostheses showed more equitable stress distribution and most likely presented a better biomechanical prognosis.

Similarly, in this study, when prostheses without gaps were delivered, there was little stress on cement-retained prostheses, but in screw-retained prostheses, stress occurred at the interproximal crest between the #1 and #2 implants. In addition, when prostheses with gaps were connected, in both types of prostheses, low stress (1.63 FO or less) occurred in the apex or the cervical area, which is consistent with the results of Guichet and colleagues.[12] When there was a gap in the prosthesis,

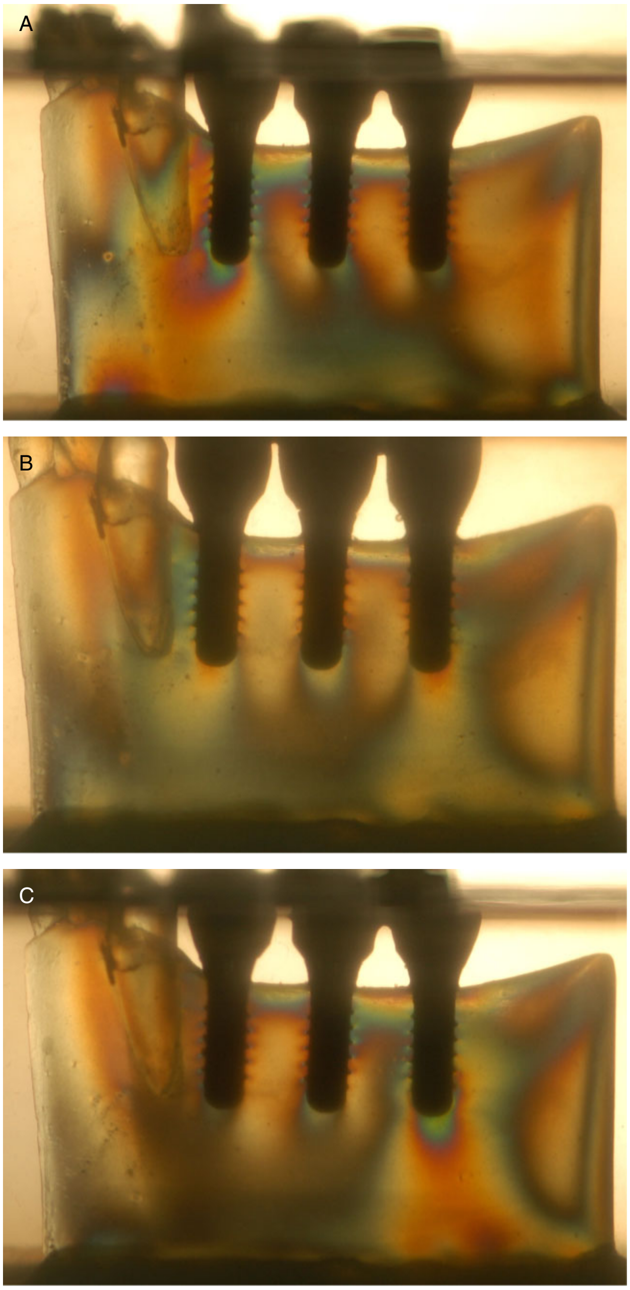

Figure 15 Stresses produced by the screw-retained fixed partial denture (FPD) with a 100-µm gap on the #2 and #3 implants under a 134-N load at P1, P2, and P3.

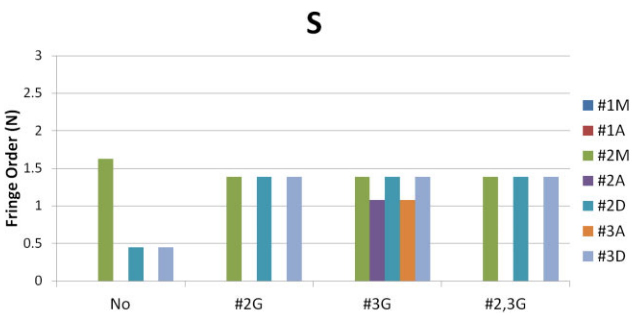

Figure 16 Maximum fringe order around three implants connected by the four types of screw-retained fixed partial dentures (FPDs) after screw fastening.

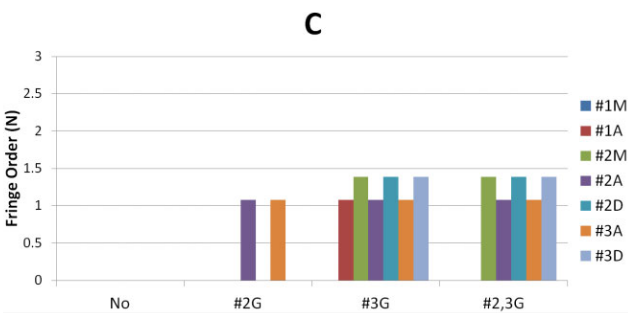

Figure 17 Maximum fringe order around three implants connected by the four types of cement-retained fixed partial dentures (FPDs) after cement setting.

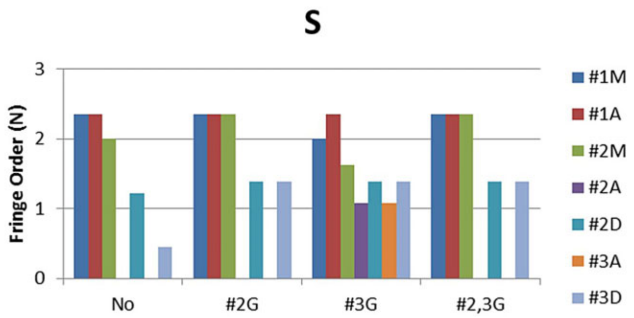

Figure 18 Maximum fringe order around three implants connected by the four types of screw-retained fixed partial dentures (FPDs) under a 134-N load at P1.

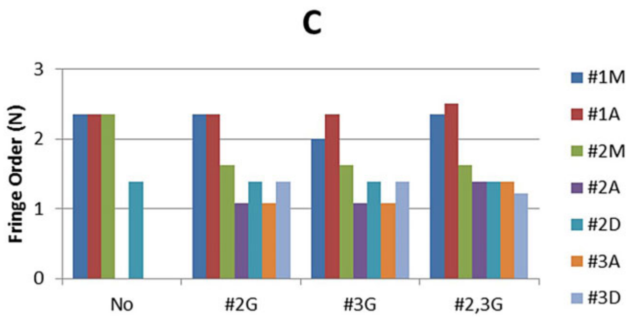

Figure 19 Maximum fringe order around three implants connected by the four types of cement-retained fixed partial dentures (FPDs) under a 134-N load at P1.

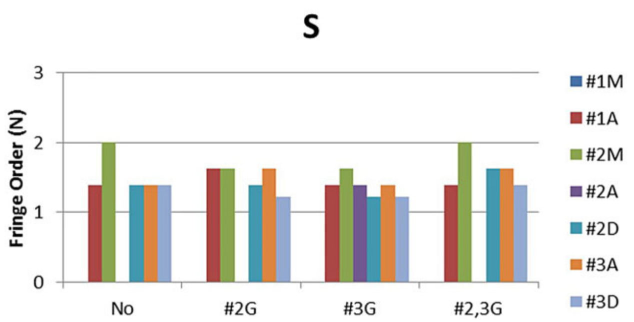

Figure 20 Maximum fringe order around three implants connected by the four types of screw-retained fixed partial dentures (FPDs) under a 134-N load at P2.

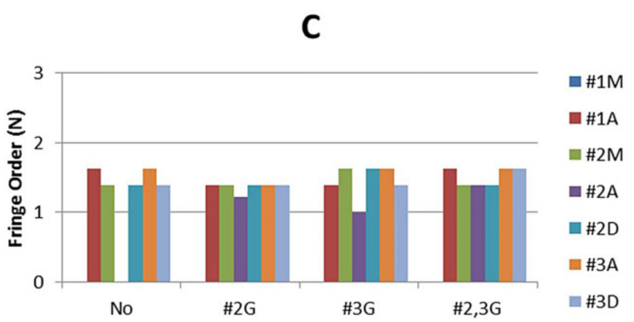

Figure 21 Maximum fringe order around three implants connected by the four types of cement-retained fixed partial dentures (FPDs) under a 134-N load at P2.

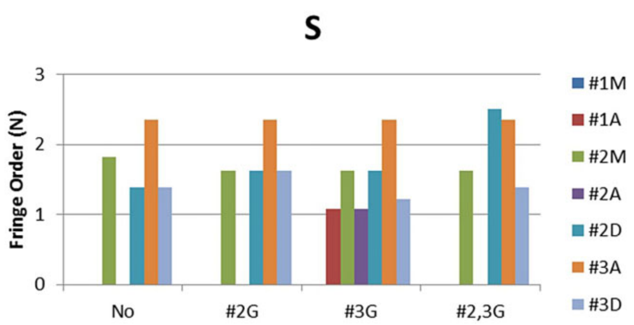

Figure 22 Maximum fringe order around three implants connected by the four types of screw-retained fixed partial dentures (FPDs) under a 134-N load at P3.

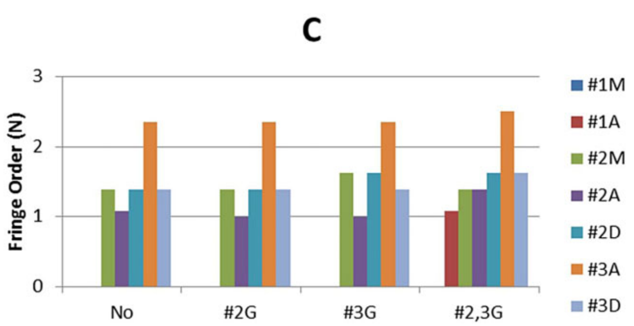

Figure 23 Maximum fringe order around three implants connected by the four types of cement-retained fixed partial dentures (FPDs) under a 134-N load at P3.

even in the cement-retained FPD, stress occurred in the supporting tissues around the implant, and passive fit in the implant prostheses was not possible. As the stress that occurred during prosthesis connection was minimal, the stress increase with the gap–prosthesis connection was also low.

In the finite element analysis study, Karl and colleagues[16] reported that the stress during prosthesis fixation by screws or cement was 5 to 30 MPa in cortical bone and 2 to 5 MPa in trabecular bone. This is equivalent to 200 N of loading, and it is not significant enough to deteriorate osseointegration, given that it is within the realm of the bone's adaptation ability.

Carr and colleagues[17] studied the response of bone to implants in the supporting tissues according to the different levels of prosthesis fit. In screw-retained prostheses, the groups were divided into prostheses with or without gaps, and the surface tensile stresses were analyzed. There was no significant difference between the two groups. Occlusal forces were not employed in their experiment, which may have been why the effect of prosthesis gap was not evident.

Jemt and Book[8] conducted a prospective study on the fit of fixed prostheses and concluded that none of the prostheses that they investigated exhibited passive fit. However, even when the prostheses did not have perfect fit, there was no evidence of increased bone loss after a 5-year follow up. These authors reported that the mean prosthetic misfit in edentulous maxillae restored with full-arch fixed prostheses was 100 μm. The average gap was 111 μm in the 1-year group and 91 μm in the 5-year group. They claimed that implant prostheses may tolerate some gaps and show long-term stability without bone resorption after 5 years of function. Based on their results, in the present study, a 100-μm gap was created between the implant abutment and the crown, and the effect of the marginal gap was investigated.

A 134-N load directed upon the #1 implant was borne nearly entirely by the #1 and #2 implants, and there was very little stress transfer to the #3 implant. Stresses on the #1 implant produced the highest stresses (2.35 FO) at the apical region and the mesial crest. There was no large difference in the maximum stress intensity or distribution between the screw-retained and cement-retained FPDs. Similar patterns were shown when loading was placed on the #3 implant. When the loading was placed on gap prostheses, the stress on the loaded implant did not decrease, whereas stress on the other implants increased, thereby increasing the general stress. A 134-N load directed upon the #3 implant with a #2, 3 gap prosthesis produced the highest stress (2.5 FO) at the apical region of the loaded implants. This distribution indicated a distal tipping of the posterior implants. These results were similar to the results of Itoh and colleagues.[18]

Cehreli and Acka[19] reported photoelastic results when cement-retained three-unit FPDs were connected to two ITI implants and a comparatively low load of 100 N was placed. High stresses of 2.65 and 3.0 FO were shown in the supporting bone of the loaded implant. In contrast, the other implant, which was not directly under load, showed minimal stress of 1 FO. As was the case in the present study, the loaded implant exhibited higher stress. These authors also recommended using narrow-diameter ITI implants only where low occlusal force is expected, as a high stress of 3.65 FO was shown in narrow-diameter implants.

Splinted restorations shared the occlusal loads and distributed the stresses more evenly between the implants than nonsplinted restorations when force was applied. The load-sharing effect was most evident on the middle implant.[20] In this study, when a 134-N load was placed on the #2 implant, the stress was distributed to adjacent implants. A stress of less than 2 FO was detected, which was the lowest level of stress among the three loading conditions. The gap in the prostheses increased the stresses in the adjacent implants, and loading enhanced the effect of the prosthesis' misfit. In this study, based on the study by Watanabe and colleagues,[14] the screws were tightened in the order of the #2, #1, and #3 implants, and the stress appeared to be distributed more when the #2 (middle) implant was tightened first.

Markarian and colleagues[21] conducted photoelastic analyses on a well-fitting and ill-fitting three-unit FPDs with a 150-μm vertical gap on the middle implant. The placement of an ill-fitting FPD using a 20-Ncm torque resulted in higher stress on the side of the adjacent implants, and middle implant loading with 100-N increased preload stress patterns resulted in the tendency for rotation in the lateral and central implants rather than transferring forces axially. Their photoelastic pattern was very different from our middle implant loading pattern. They explained the ill-fitting stress patterns with the deformation theory by Jemt and Lekholm.[22] However, 150-μm deformation occurred with a 1-mm misfitted framework in their work. In addition, the screw-retained FPDs in this study were fabricated with gold cylinders on synOcta abutments and connected with a low torque of 15 Ncm during screw tightening, which may have resulted in different patterns from the conical abutment (Conexão, São Paulo, Brazil) used in their study.

Kunavisarut and colleagues[9] employed three-dimensional FEA to study the effect of misfit prostheses, cantilever prostheses, and various occlusal forces on the stress distribution, and reported that as the gap was closer to the loading point, the stress increased, and the effect of gaps on stress distribution became clearer with loading. In two implant-supported, two-unit FPDs, the stress in the supporting bone increased 6% in mesial gap prosthesis loading, whereas it increased 32% upon distal gap prosthesis loading. In this study, when the #3 implant was loaded in a cement-retained prosthesis, the stress was greater with the #3 gap prosthesis compared with the #2 gap prosthesis, but the difference was not as large as 32%.

Implant prostheses may be retained by either screw or cement, and there is still no evidence that one method is superior to the other. Tonella and colleagues[23] evaluated the stress distribution of different retention systems (screwed or cemented) associated with different prosthetic connections (external hexagon, internal hexagon, and Morse taper) in implant-supported three-unit FPDs via photoelasticity. These authors concluded that the cemented retention system presented better stress distribution, and the internal hexagon implant was more favorable from a biomechanical standpoint. In their study, two implant-supported three-unit FPDs were tested, and when a 100 N axial load was placed on Morse taper implants, the screw-retained type exhibited stress of 21 FO, and the cement-retained type exhibited stress of 15 FO. Alternatively, Heckmann and colleagues[13] studied the precision of both screw-retained and cement-retained prostheses according to different fabrication methods, and both types exhibited high levels of stress, of similar amounts. They emphasized the importance of prosthesis precision, as cement-retained prostheses also showed stress due to misfit of the prostheses.

Recently, Sailer and colleagues[24] assessed the 5-year survival rates and incidences of complications of cement- and screw-retained implant reconstructions. These authors found that none of the fixation methods was clearly advantageous over the other, but the screw-retained reconstructions appeared to be preferable. Cemented reconstructions exhibited more serious biological complications, and screw-retained reconstructions exhibited more technical problems. Screw-retained reconstructions are more easily retrievable than cemented reconstructions, and technical and eventually biological complications can thus be treated more easily.

According to the results of this study, the level of misfit and stress depends not only on the type and loading of the prostheses but also on the bone quality, implant position, shape of the dental arch, diameter and length of the implant, the implant's surface characteristics, and the shape of the prostheses. Therefore, although it is difficult to establish a universal criteria, it is always important to fabricate an accurate prosthesis.

CONCLUSIONS

1. When the prostheses without gaps were connected, little stress developed in the cement-retained prosthesis, whereas crestal stress developed in the screw-retained prosthesis. When there was a gap, minimal apical or coronal stress of less than 1.63 FO developed in both types of prostheses.
2. When the terminal implants were loaded, the stress pattern and magnitude in screw-retained and cement-retained prostheses were similar. In both types, the highest stresses of more than 2.35 FO developed on the apex and coronal parts of the loaded implants.
3. When the middle implant was loaded, in both prosthesis types, stress dispersed to adjacent implants.
4. Screw-retained FPDs with gaps exhibited a wider range of stresses on the coronal portion of adjacent implants than cement-retained FPDs. However, severe misfit of prostheses caused nonaxial stress transfer to the adjacent implants in the cement-retained FPDs. When there were more than two gaps, the highest stress (2.5 FO) developed at the apex of the loaded implants, and the stress pattern changed in cement-retained FPD.

ACKNOWLEDGMENTS

This paper was supported by Wonkwang University in 2013. [Correction added September 23, 2013, after first online publication: Acknowledgments added.]

REFERENCES

1. Lekholm U, Adell R, Brånemark P-I. Complications. In: Brånemark P-I, Zarb GA, Albrektsson T, eds. Tissue-integrated prostheses: osseointegration in clinical dentistry. Chicago, IL: Quintessence, 1985:233–240.
2. Assif D, Marshak B, Schmidt A. Accuracy of implant impression techniques. Int J Oral Maxillofac Implants 1996; 11:216–222.
3. Pietrabissa R, Contro R, Quaglini V, Soncini M, Gionso L, Simion M. An in vitro study on compensation of mismatch of screw vs. cement-retained implant supported fixed prostheses. Clin Oral Implants Res 2000; 11:448–457.
4. Skalak R, Zhao Y. Interaction of force-fitting and surface roughness of implants. Clin Implant Dent Relat Res 2002; 2:219–224.
5. Millington ND, Leung T. Inaccurate fit of implant superstructures. Part 1: stresses generated on the superstructure relative to the size of fit discrepancy. Int J Prosthodont 1995; 8:511–516.
6. Kan JY, Rungcharassaeng K, Bohsali K, Goodacre CJ, Lang BR. Clinical methods for evaluating implant framework fit. J Prosthet Dent 1999; 81:7–13.
7. Jemt T. In vivo measurements of precision of fit involving implant-supported prostheses in the edentulous jaw. Int J Oral Maxillofac Implants 1996; 11:151–158.
8. Jemt T, Book K. Prosthesis misfit and marginal bone loss in osseointegrated implant patients. Int J Oral Maxillofac Implants 1996; 11:620–625.
9. Kunavisarut C, Lang LA, Stoner BR, Felton DA. Finite element analysis on dental implant-supported prostheses without passive fit. J Prosthodont 2002; 11:30–40.
10. Misch CE. Screw-retained vs cement-retained implant-supported prostheses. Pract Periodontics Aesthet Dent 1995; 9:15–18.
11. Hebel KS, Gajjar RC. Cement-retained versus screw-retained implant restorations: achieving optimal occlusion and esthetics in implant dentistry. J Prosthet Dent 1997; 77: 28–35.
12. Guichet DL, Caputo AA, Choi HJ, Sorensen JA. Passivity of fit and marginal opening in screw- or cement- retained implant fixed partial denture designs. Int J Oral Maxillofac Implants 2000; 15:239–246.
13. Heckmann SM, Karl M, Wichmann MG, Winter W, Graef F, Taylor TD. Cement fixation and screw retention: parameters of passive fit. An *in vitro* study of three-unit implant-supported fixed partial dentures. Clin Oral Implants Res 2004; 15:466–473.
14. Watanabe F, Uno I, Hata Y, Neuendorff G, Kirsch A. Analyses of stress distribution in a screw-retained implant prosthesis. Int J Oral Maxillofac Implants 2000; 15:209–218.
15. Kim KS, Kim YL, Bae JM, Cho HW. Biomechanical comparison of axial and tilted implants for mandibular full-arch fixed prostheses. Int J Oral Maxillofac Implants 2011; 26:976–984.
16. Karl M, Winter W, Taylor TD, Heckmann SM. Fixation of 5-unit implant-supported fixed partial dentures and resulting bone loading: a finite element assessment based on in vivo strain measurements. Int J Oral Maxillofac Implants 2006; 21:756–762.
17. Carr AB, Gerard DA, Larsen PE. The response of bone in primates around unloaded dental implants supporting prostheses with different levels of fit. J Prosthet Dent 1996; 76:500–509.
18. Itoh H, Caputo AA, Kuroe T, Nakahara H. Biomechanical comparison of straight and staggered implant placement configurations. Int J Periodontics Restorative Dent 2004; 24:47–55.
19. Cehreli M, Akca K. Narrow-diameter implants as terminal support for occlusal three-unit FPDs: a biomechanical analysis. Int J Periodontics Restorative Dent 2004; 24:513–519.
20. Guichet DL, Yoshinobu D, Caputo AA. Effect of splinting and interproximal contact tightness on load transfer by implant restorations. J Prosthet Dent 2002; 87:528–535.
21. Markarian RA, Ueda C, Sendyk C, Laganá D, Souza R. Stress distribution after installation of fixed frameworks with marginal gaps over angled and parallel implants: a photoelastic analysis. J Prosthodont 2007; 16:117–122.
22. Jemt T, Lekholm U. Measurements of bone and framework deformations induced by misfit of implant superstructures: a pilot study in rabbits. Clin Oral Implants Res 1998; 9:272–280.
23. Tonella BP, Pellizzer EP, Ferraço R, Falcón-Antenucci RM, Carvalho PS, Goiato MC. Photoelastic analysis of cemented or screwed implant-supported prostheses with different prosthetic connections. J Oral Implantol 2011; 37:401–410.
24. Sailer I, Mühlemann S, Zwahlen M, Hämmerle CH, Schneider D. Cemented and screw-retained implant reconstructions: a systematic review of the survival and complication rates. Clin Oral Implants Res 2012; 23(Suppl 6): 163–201.