In Vitro Stress Analyses of Dental Implants Supporting Screw-Retained and Cement-Retained Prostheses

Wook Dong Kim, DDS,* Zhimon Jacobson, DDS, DMD, MsD,** Dan Nathanson, DMD, MsD***

The use of cement-retained implant prostheses is increasing because of improved occlusal anatomy, esthetics, and simplified laboratory procedures.1-3 Little is known about the biomechanics of cement-retained implant prostheses compared with that of screw-retained implant prostheses. To date, almost all studies of implant biomechanics have focused on screw-retained prostheses. English1 claimed that cement-retained prostheses distributed occlusal loads more evenly to abutments and absorbed shocks more effectively because of the presence of cement. Misch4 stated that the principles of gradual loading of bone with implant prostheses were best demonstrated in the cement-retained prostheses. However, there is no scientific research to support either of these claims. This study used photoelastic and strain gauge analysis to compare the loads transferred to implants through screw-retained and cement-retained implant prostheses.

Occlusal loading of osseointegrated implants is one of the determining factors in the long-term success of an implant treatment.5,6 In a six-year clinical study, Lindquist et al7 reported that clenching teeth and poor oral hygiene significantly influenced bone loss. Quirynen et al8 also reported in a three-year follow-up study of Bränemark implants that excessive marginal bone loss and/or fixture failure correlated positively with the presence of parafunctional overload. Various methods of reducing stress to the prosthetic components and implant fixture/bone complex have been advocated with respect to the type of occluding surface and the incorporation of resilient elements within the abutment/fixture complex. It has been suggested that acrylic resin, considered to be a shock-absorbing material, is more beneficial to the implant-bone interface in impact loading conditions than porcelain fused to metal.5,9 On the other hand, Ismail10 suggested in his finite element analysis study that the use of resin teeth as a shock absorber may not be valid. In their two-year clinical study of 509 implants supporting fixed partial dentures, Naert et al11 reported that marginal bone loss was not related to the type of occlusal material. Based on theoretical mathematical calculation, Richter recommended the incorporation of a soft cushioning element within the implant/abutment complex.12 Using finite element analysis, Watanabe et al13 showed that the propagation of stress to bone could be reduced by the use of an intramobile element. However, McGlumphy et al14 questioned the effectiveness of the intramobile element by showing that an 18 mm cantilevered fixed partial denture supported by two implants with plastic internal elements caused deflections equal to that caused by one with titanium internal elements. He concluded that the abutment screw can withstand more stress than the intramobile element.

Using photoelastic models, Deines et al15 studied the force distribution of three different implant designs. Employing vertical load, stresses were developed all around...
the implant surface, with greater stresses around the apex in both the threaded and the non-threaded screw-type implants. With the cylinder-type implant, stresses were concentrated around the apex with very little stress around the lateral surface. In lateral force conditions, in all types of implants, stresses were concentrated within the marginal bone area contralateral to the applied load and in the apical third of the loaded side. Using photoelastic and strain gauge analysis, Clelland et al.\textsuperscript{16} found that the compressive stress nearly doubled as the angulation of the load increased from 0 to 20 degrees in the cervical area of the fixture on the side opposite to the applied load. Wylie et al.\textsuperscript{17} also reported similar results using a three-dimensional photoelastic model of the maxilla.

Many biomechanical studies of implants have been devoted to investigating the effects of load application to cantilevered prostheses. Skalak\textsuperscript{2} stated that the introduction of cantilever forces might increase the maximum load per screw from 1.5 to 2 times the applied load. White et al.\textsuperscript{18} studied the effect of cantilever length on stress transfer to the implant and supporting structure by using a three-dimensional photoelastic model of a human mandible. As loads were applied to cantilevers of various lengths, the highest stresses were concentrated at the ridge crest adjacent to the distal surface of the closest implant to the loaded side. Minimal load was transferred to the third, fourth, and fifth implants from the loading point. The above study was consistent with the Patterson et al.\textsuperscript{19} study that used strain gauges bonded to the abutments of implants. Patterson et al. report that the bending moment was highest on the abutment adjacent to the distal cantilever. Increasing the cantilever length increased the maximum compressive loads on the abutment adjacent to the distal cantilever but had little effect on the tensile axial loads on the anterior abutments. Rangert et al.\textsuperscript{20} reported in their retrospective clinical study that bending overload caused by the combination of cantilevers and bruxism or heavy occlusal forces was the main reason for the implant fracture.

**MATERIALS AND METHODS**

Photoelastic stress analysis is based on the ability of certain transparent materials to exhibit colorful patterns when loaded and viewed with polarized light.\textsuperscript{21} This array of colored patterns is called isochromatic fringes. The larger the number of fringes, the higher the stress intensity; and the closer the fringes are to each other, the higher the stress concentration. Strain gauges use the principle that certain elements undergo a change of electric resistance when they are subjected to strain.\textsuperscript{21} Tension increases resistance, and compression decreases it. This change of resistance can be measured at the point at which the strain gauge is bonded.

An 80- × 100- × 9.5-mm photoelastic model was cut from a block of photoelastic resin (Measurement Group Inc., Raleigh, NC). After being cured, the edge of the model was smoothed consecutively using 400 and 600 grit sandpaper (3M, St. Paul, MN), until the residual stress fringes were completely removed. For the fixed partial denture and cantilevered prosthesis study, two implant sites were prepared to receive 13- × 3.75-mm screw type implants (ST313, Implant Innovations, West Palm Beach, FL) using a 9/64 inch diameter carbide drill. The two holes were 7 mm apart and 12 mm deep.\textsuperscript{22} The implants were coated with PCM-1 adhesive (Measurement Group) and inserted into the holes, which were also filled with adhesive. Another photoelastic model with one implant fixture was made using the same materials and methods for the single crown test.

Ten wax patterns were made using gold UCLA-type abutments (GUCH1, Implant Innovations) to cast custom abutments. The custom abutment was 6 mm in height. The diameter at the cervical area was 5.6 mm, with an 8 taper. After waxing, wax patterns were invested using Beauty-Cast (Whipmix Co., Chicago, IL) and cast at 900°F with Ney76 palladium alloy (Ney Dental International, Bloomfield, CT). The casting was milled again to an 8 axial wall angulation using a milling carbide bur (H356S-050, Brasseur, Savannah, GA) and polished.

Using the photoelastic model as a master model, a resin pattern for the screw-retained implant prosthesis was fabricated with GC pattern resin (GC America, Chicago, IL). The resin pattern was an 8-mm high, 21-mm long, and 7-mm wide cantilever-type fixed prosthesis with flat surfaces. The cantilevered section was 2.5 mm thick. Four more resin patterns for the screw-retained prostheses were made in the same dimensions as the first. Five resin patterns for the cement-retained implant prostheses were made in a similar fashion over the custom abutments. The shape and size of the cement-retained prosthesis were the same as that of the screw-retained prosthesis. Resin patterns were invested and cast using the same material and methods as the custom abutment fabrication. A casting ring liner and the hygroscopic expansion technique were used for the cement-retained prosthesis. After casting, the prostheses fit to the custom abutments was checked individually using Fit Checker (GC America), and high spots were adjusted to achieve an optimal fit.

Because a passive fit was not achieved after the casting, the metal frameworks of both types of prostheses were sectioned and soldered.\textsuperscript{23-25} A stone model with two implant lab analogs and a vertically embedded plastic ruler on one side was made to standardize the dimensions of the prostheses. Using this stone model, force application points were marked on the prostheses. For the single crown, the loading point was 2.5 mm from the center of the implant fixture. The loading point for the two-implant-supported fixed partial denture was 2.5 mm mesial from the center of the distal implant (implant 1). The loading point for the cantilevered fixed prostheses was 8 mm from the center of the distal implant (implant 1) (Fig. 1).

An Instron universal testing machine (Instron, Canton, MA) with a 1000-N load cell was used to apply a
110-N vertical load at a speed of 0.2 mm/min. This load was chosen after the pilot study. When more than 140-N load was applied, the cement layer of the cantilevered cement-retained prosthesis started to break and the prosthesis separated from the custom abutments.

The implant abutment screws were tightened at 30 N-cm using a torque wrench and were retightened after 10 minutes to compensate for the settling of the screws. After the custom abutments were screwed onto the implant fixtures, the cement-retained prostheses were cemented onto the custom abutments using provisional cement (Tempbond, Kerr, Romulus, MI) and polycarboxylate cement (Durelon, ESPE, Germany).

To deliver the constant force for cementation, a 50-N load was applied for 5 minutes using the Instron machine. At the time of cementation, the screw access holes of the custom abutments were filled with the cement to maximize the retention.

The photoelastic analysis was accomplished using circular polarizing filters (Measurement Group) and a white light source. Color photographs were taken for each sample. As a basis for comparison, photographs of the unloaded models were also made. The distribution and relative magnitude of the stress fringes were analyzed using the photographs of each sample. The fringe orders were calculated based on Table 1. A 1-way ANOVA and a Student-Newman-Keuls test was performed for statistical analysis.

A strain gauge (EA-06–015EH-120, Measurement Group Inc.) was bonded 1 mm below the neck of an implant lab analog (ILA20, Implant Innovations). Lab analogs with the strain gauges were aligned to demonstrate maximum stress level and embedded into the epoxy resin. A bondable terminal was installed next to the lab analog, and the lead wires and the extension wires were soldered to it. The extension wires were connected to a strain indicator (3800 wide range strain indicator, Measurement Group) in a half Wheatstone bridge arrangement. The strain indicator was balanced for each gauge before each measurement. Specimens were loaded using the same procedure as with the photoelastic analysis, and the strain indicator readings were recorded and analyzed.

The vertical deflection of the prostheses was measured in terms of the overall distance of the downward movement of the force probe of the Instron machine. This measuring was accomplished during the photoelastic test. The deflections recorded by the Instron machine were compared for statistical analysis.

RESULTS

Photelastic Test

In the single crown test, the overall patterns of isochromatic fringes in all three types of crowns (screw-retained, permanent-cement-retained, and provisional-cement-retained) were analyzed using the photographs of each sample. The fringe orders were calculated based on Table 1.

A 1-way ANOVA and a Student-Newman-Keuls test was performed for statistical analysis.

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<tr>
<th>Color</th>
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<tr>
<td>White</td>
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</tr>
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<tr>
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<td>Red</td>
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<tr>
<td>Green</td>
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<tr>
<td>Pink/green transition</td>
<td>5.00</td>
</tr>
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</table>

Table 1. Fringe Orders
Fig. 2. Isochromatic stress fringe patterns of a screw-retained single implant crown. A, B: Stress fringe order measuring points.
Fig. 3. Isochromatic stress fringe patterns of a permanent-cement-retained single implant crown.
Fig. 4. Isochromatic stress fringe patterns of a provisional-cement-retained single implant crown.

retained) were relatively similar and only the stress intensity was different (Figs. 2, 3, and 4). The highest stress was concentrated in the coronal third of the loaded side. The middle third was relatively stress-free. In the apical third, relatively moderate stress fringes were observed. Stress fringes of the coronal third of the loaded side and fringes of the apex were chosen for quantitative stress analysis. The provisional-cement-retained crown showed less stress fringes than the screw-retained and the permanent-cement-retained crown ($P < 0.05$). There was no difference between the screw-retained and the permanent-cement-retained crown ($P < 0.05$). The results are summarized in Table 2 and Figure 5.

For the fixed partial denture, the stress fringes at the apex of both implants were chosen for analysis. The highest stress concentration was observed around the apical aspect of implant I (point A) in all prostheses (Figs. 6, 7, and 8). Implant II showed little stress compared with implant I. No difference was found between the three different types of prostheses at both point A and B ($P < 0.05$). The results are summarized in Table 3 and Figure 9.

Three points around the implant fixtures were evaluated for photoelastic analysis of the cantilevered prosthesis (Figs. 10, 11, and 12). In the provisional-cement-retained prosthesis, the loaded side of the coronal one third of implant I showed the highest stress concentration. In the screw-retained and permanent-cement-retained prosthesis, the highest stresses were concentrated at the apex of implant I. At points A and B, there were no differences between the screw-retained and the permanent-cement-retained prostheses, but the provisional-cement-retained prostheses showed significant differences compared with the other types ($P < 0.05$). At point C, there was no significant difference be-

| Table 2. One-Way ANOVA for Photoelastic Fringe Orders of the Single Crown* |
|---------------------------------|---|---|---|---|---|
| Source of Variation             | SS | df | MS  | F   | $P$ value | F crit |
| Point A                          |    |    |     |     |           |        |
| Between groups                   | 6.87| 2 | 3.43| 200.36| 0.00      | 3.35   |
| Within groups                    | 0.46| 27| 0.02|       |           |        |
| Total                            | 7.33| 29|     |       |           |        |
| Point B                          |    |    |     |     |           |        |
| Between groups                   | 1.10| 2 | 0.55| 30.05| 0.00      | 3.35   |
| Within groups                    | 0.50| 27| 0.02|       |           |        |
| Total                            | 1.60| 29|     |       |           |        |

* MS, mean squares; SS, sum of squares.
between the three types of prostheses. Test results are shown in Table 4 and Figure 13.

**Strain Gauge Test**

For the single crown test, the screw-retained crowns and the permanent-cement–retained crowns exhibited significantly higher strains than the provisional-cement–retained crowns ($P < 0.05$). In the fixed partial denture test, there were no significant differences between the three different types of prostheses in both implants I and II. In the cantilevered prosthesis, the provisional-cement–retained prostheses showed the highest and the permanent-cement–retained prostheses showed the second highest strain levels at the neck of implant I. The screw-retained prostheses showed significantly lower strain levels than the others ($P < 0.05$). At implant II, the provisional-cement–retained prostheses showed higher strain levels than the others. There was no difference between the screw-retained and permanent-cement–retained prostheses. The results of the strain gauge tests are summarized in Table 5 and Figure 14.

**Deflection of the Prosthesis**

In the single crown test, the provisional-cement–retained crowns showed significantly higher deflection than the others ($P < 0.05$). In the fixed partial denture test, there was no significant difference. In the cantilevered prosthesis, the cement–retained prostheses showed significantly higher deflection than the others ($P < 0.05$). There was no significant difference between the screw-retained and the permanent-cement–retained prostheses. The results are summarized in Table 6 and Figure 15.

**DISCUSSION**

Unlike human bone, which is constituted of cortical and cancellous bone, a photoelastic model is a homogenous plastic mass. Therefore, the stress magnitude and the stress

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**Fig. 5.** Photoelastic stress fringe order measurements of the single crown tests.

**Fig. 6.** Isochromatic stress fringe patterns of a screw-retained fixed partial denture.

**Fig. 7.** Isochromatic stress fringe patterns of a permanent-cement–retained fixed partial denture.

**Fig. 8.** Isochromatic stress fringe patterns of a provisional-cement–retained fixed partial denture.
Table 3. One-Way ANOVA for Photoelastic Fringe Orders of Fixed Partial Denture

<table>
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<tr>
<th>Source of Variation</th>
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<th>df</th>
<th>MS</th>
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<th>P value</th>
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<td>Point A</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Between groups</td>
<td>0.13</td>
<td>2</td>
<td>0.07</td>
<td>1.89</td>
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<td>3.89</td>
</tr>
<tr>
<td>Within groups</td>
<td>0.42</td>
<td>12</td>
<td>0.04</td>
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<tr>
<td>Total</td>
<td>0.56</td>
<td>14</td>
<td></td>
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</tr>
<tr>
<td>Point B</td>
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</table>

Fig. 9. Photoelastic stress fringe order measurements of the fixed partial dentures.

patterns of real bone might be different from the photoelastic model. However, the locations and the general stress patterns would not be substantially different. The positive relationship between the in vitro photoelastic model findings and the clinical research findings have been proven by many studies. The simulated occlusal force (110 N) used in this study was in the range normally found during mastication by human subjects with natural teeth or with implant-supported prostheses. The main advantage of a screw-retained prosthesis over a cement-retained prosthesis is its retrievability. However, if a provisional cement is used as a luting agent, retrievability can also be achieved in a cement-retained prosthesis. Adequate retention of the prosthesis can be assured by adjusting the taper of the custom abutment with the milling procedure. Considering that a pre-manufactured implant abutment for cement often has a taper in excess of 25 degrees, the 8 degree of taper of the custom abutment used in this study is in the acceptable range. Some authors recommended the use of a permanent cement instead of the provisional cement. In this case, the retrievability of the prostheses should be severely restricted.

In the single crown test, the loading point was 2.5 mm from the center of the implant fixture, which means it was 0.6 mm off the edge of
Table 4. One-Way ANOVA for Photoelastic Fringe Orders of Cantilevered Prostheses

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<td>Point B</td>
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</table>

the implant fixture. Thus, this implant fixture received a lateral force even though the vertical force was applied on a flat surface. Both the photoelastic and the strain gauge tests showed that the provisional-cement–retained crown transferred less stress to the implant fixture and surrounding structure (photoelastic resin) than the others. And the provisional-cement–retained crown exhibited more deflection. This difference can be attributed to the presence of the cement layer and the properties of the provisional cement. In the fixed partial denture test, no difference was found between the three different types of prosthesis in all tests performed. This result can be attributed to the limited number of the sample size. In the photoelastic test of the cantilevered prosthesis, the provisional-cement–retained prosthesis showed higher stresses than the others in the coronal aspect of the distal part of implant I. This result is consistent with the strain gauge test, which indicated that the cement-type suffered higher strain levels at the necks of both implants. In the screw-type, the tipping of the cantilevered portion was offset by the abutment screws of implants I and II. The tipping of the provisional-cement–retained prosthesis was restricted by

Fig. 13. Photoelastic stress fringe order measurements of the cantilevered prostheses.

Fig. 14. Microstrains of the prostheses. Positive value, compressive stress; negative value, tensile stress

Fig. 15. Deflections of prostheses.
Table 5. One-Way ANOVA for Microstrains

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<td>26364.93</td>
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deflected more than that of the screw-retained prosthesis. This tipping also resulted in the higher stress in the cervical area in the cement-type prosthesis. The tipping of the permanent-cement-retained prosthesis was almost the same as the screw-retained prosthesis because of the high bond strength of the permanent cement. At the apical portion of implants, the screw-type cantilevered prosthesis showed more stress fringes. This indicates that the screw-type cantilevered prosthesis transfers more stress in an axial direction. This experiment might yield different results if the custom abutment taper or the thickness of the cement layer were changed. Further study will be needed to see whether these variables will affect the result.

CONCLUSION

This study compares the loads transferred to the implant fixtures through the provisional-cement–retained, permanent-cement–retained, and the screw-retained prostheses using photoelastic and strain gauge tests. The deflections of the prostheses at the time of loading were also

Table 6. One-Way ANOVA for Deflections of Prostheses

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<th>Source of Variation</th>
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<th>MS</th>
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</table>

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measured. In the single crown situation, the provisional-cement–retained implant crown transferred less stress to the implant fixture and supporting structure (photoelastic material) than the screw-retained and the permanent-cement–retained implant crown when a vertical force was applied. And the provisional-cement–retained crown deflected more than the other types of crowns when a same vertical force was applied.

In the two-implant supported fixed partial denture test, the force was applied between two implants but closer to one implant than the other. No difference was found between the three different types of prostheses.

In the photoelastic test of the two-implant supported distal cantilevered prostheses, the provisional-cement–retained prostheses developed higher stress around the distal cervical portion of the distal implant than the others. The screw-retained and the permanent-cement–retained prostheses developed higher stresses around the apex of both implants. This result suggests that the screw-retained and the permanent-cement–retained cantilevered prosthesis transferred more stress apically than the provisional-cement–retained prostheses. In the strain gauge test, the provisional-cement–retained cantilevered prosthesis caused more compressive stress on the distal cervical part of the distal implant and more tensile stress on the mesial cervical part of the mesial implant than the others. The provisional-cement–retained cantilevered prostheses showed more deflection of the cantilevered portion than the others. In all tests performed, the permanent-cement–retained prosthesis behaved almost the same as the screw-retained prosthesis.

REFERENCES

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SCHLÜSSELWÖRTE: Vorläufig zementierte Prothese, fotoelastische Analyse, Belastungsmesser, geschient Implantat, Stiftprothese, Einzelzahnimplantate, Streßverteilung
ABSTRACTO: Se realizó un análisis fotoenástico y de medición de la tensión para evaluar la tensión transferida a los implantes a través de prótesis retenidas provisionalmente con cemento, retenidas permanentemente con cemento y retenidas con tornillos. Las deflexiones de las prótesis en el momento de carga también se midieron. En la prueba de una sola corona, las coronas retenidas provisionalmente con cemento transferieron menos tensión. En la prueba de la dentadura parcial fija de dos unidades, no hubo diferencias entre los tres tipos de prótesis. En las prótesis voladizas distales apoyadas de dos implantes, las prótesis retenidas provisionalmente con cemento o por tornillos crearon más tensión alrededor del ápice de ambos implantes. Las prótesis retenidas permanentemente con cemento actuaron casi igual que las con tornillos.

PALABRAS CLAVES: Prótesis retenida provisionalmente con cemento, análisis fotoenástico, análisis de medición de la tensión, implantes con férula, prótesis voladiza, implantes de un solo diente, distribución de la tensión

SINOPSE: Uma análise fotoenástico e de medição de tensão foi efetuada para avaliar o estresse transferido aos implantes por próteses fixadas com cimento provisório, fixadas com cimento permanente e fixadas com parafuso. Também foram medidas as deflexões das próteses no momento da colocação. Em um teste de coroa simples, as coroas fixadas com cimento provisório transferiram menos estresse. No teste com dentadura dupla parcial fixa, não houve diferenças entre os três tipos diferentes de próteses. Nas próteses cantiléveres distais apoiadas por dois implantes, as próteses do tipo cimento com parafuso e as fixadas com cimento permanente apresentaram mais estresse em volta do ápice de ambos os implantes. As próteses fixadas com cimento permanente tiveram a mesma reação que as do tipo com parafuso.

PALAVRAS-CHAVES: prótese fixada com cimento provisório, análise fotoenástica, análise de medição de tensão, implantes de restauração fixa, próteses cantiléveres, implantes de dente simples, distribuição do estresse

ネジ固定またはセメント固定のデンタルインプラント支持補綴についての生体外ストレス分析

著者：ウック・ドン・キム、DDS、ジーマン・ジェーコブソン、DDS、DMD、MsD**
ナッダ・ネーサンソン、DMD、MsD**

概要：
セメント固定、セメント永久固定、ネジ固定の3種の補綴について、インプラントに伝達されるストレスを、光弾性とストレインゲージ法で測定・評価した。補綴装着時のたわみを計測した。シングルクラウンテストでは、セメント固定クラウンがストレス伝達が一番小さかった。ツーユニットの固定部分観察では、2つの方法の結果に何ら違いが見出されなかった。2つのインプラントで支持された遠位片持ち型の補綴では、ネジ固定とセメント永久固定の補綴が両インプラントの頸部より大きいストレスを発生した。セメント永久固定の補綴は、ネジ固定の補綴とほぼ同様の応力を見えた。

キーワード：
セメント固定補綴、光弾性分析、ストレインゲージ分析、スプリントを用いたインプラント、片持ち型補綴、単独歯インプラント、ストレス配分

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