

Strain of implants depending on occlusion types in mandibular implant-supported fixed prostheses

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PURPOSE. This study investigated the strain of implants using a chewing simulator with strain gauges in mandibular implant-supported fixed prostheses under various dynamic loads. **MATERIALS AND METHODS.** Three implant-supported 5-unit fixed prostheses were fabricated with three different occlusion types (Group I: Canine protected occlusion, Group II: Unilaterally balanced occlusion, Group III: Bilaterally balanced occlusion). Two strain gauges were attached to each implant abutment. The programmed dynamic loads (0 - 300 N) were applied using a chewing simulator (MTS 858 Mini Bionix II systems, MTS systems corp., Minn, USA) and the strains were monitored. The statistical analyses were performed using the paired t-test and the ANOVA. **RESULTS.** The mean strain values (MSV) for the working sides were 151.83 $\mu\epsilon$, 176.23 $\mu\epsilon$, and 131.07 $\mu\epsilon$ for Group I, Group II, and Group III, respectively. There was a significant difference between Group II and Group III ($P < .05$). Also, the MSV for non-working side were 58.29 $\mu\epsilon$, 72.64 $\mu\epsilon$, and 98.93 $\mu\epsilon$ for Group I, Group II, and Group III, respectively. One was significantly different from the others with a 95% confidence interval ($P < .05$). **CONCLUSION.** The MSV for the working side of Groups I and II were significantly different from that for the non-working side (Group I: $t = 7.58$, Group II: $t = 6.25$). The MSV for the working side of Group II showed significantly larger than that of Group III ($P < .01$). Lastly, the MSV for the non-working side of Group III showed significantly larger than those of Group I or Group II ($P < .01$). [J Adv Prosthodont 2011;3:1-9]

KEY WORDS. Strain, MTS machine, Implant-supported fixed prosthesis, Occlusion type

INTRODUCTION

Dental implants were introduced in the late 1960s for the rehabilitation of the completely edentulous patients.^{1,2} Through the preliminary studies on osseointegration, dental implants have been extensively used for the rehabilitation of completely or partially edentulous patients over the last three decades.^{1,3} And the use of implants has revolutionized dental treatment modalities and provided excellent long-term results.⁴ Despite high success rates reported by a vast number of clinical studies, early or late implant failures are still unavoidable.⁵ Late implant failures are observed after prosthesis delivery and are mainly related to biomechanical complications. One etiologic factor is the lateral component of force during the transmission of forces by prosthesis to dental implants. The lateral component of force is responsible for creating bending moments which have a destructive effect on the cortical bone

surrounding the implant collar and can cause complications associated with component loosening or fracture.⁵ Yet, the mechanisms responsible for biomechanical implant failures are not fully understood and the literature concerning the influences of several biomechanical factors are inconclusive.⁶

Occlusion can be critical for implant longevity because of the nature of the potential load created by tooth contacts and the impact on the attachment of the bone to the titanium implant. In the natural dentition, the periodontal ligament has the capacity to absorb stress or allow for tooth movement, but the bone-implant interface seemingly has no capacity to allow movement of the implant.^{7,8}

Vertical loads from mastication induce axial forces and bending moment and result in stress gradients in the implant as well as in the bone. A key factor for the success or failure of a dental implant is the manner in which stress is transferred to the surrounding bone.⁹

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Deflective contacts in the intercuspatal position may be responsible for excessive force development. Gibbs *et al.*¹⁰ reported that the greatest forces during mastication are exerted in the intercuspatal position. If this position is unstable, intolerably high forces can be exerted. The application of functional forces induces stress and strain within the implant-prosthesis complex and affects the bone remodeling process around implants.^{2,11} Yet, the physiologic tolerance thresholds of human jawbones are not known and some reported implant failures may be related to magnitudes of stress beyond tolerable levels.

Studies on bone biology suggest that implant overloading may lead to implant failures when implants are overloaded, high deformations (above 2000 - 3000 microstrain) occur in the bones surrounding the implants.¹² When pathologic overloading occurs (over 4000 microstrain), stress and strain gradients exceed the physiologic tolerance threshold of the bones and cause microfractures at the bone-implant interface.¹³ While overloading may be manifested by the application of repeated single loads, which causes microfractures within the bone tissue, continuous application of low loads may also lead to failure, namely, fatigue fracture. Excessive dynamic loading may also decrease bone density around the neck of implants and lead to crater-like defects.¹⁴ Accordingly, overload-associated implant failures have been reported following the first year of prosthodontic treatment.¹⁵

Horshaw and co-workers¹⁶ reported that overloading of implants resulted in an increased bone resorption around the implant collar, and a decreased percentage of mineralized bone tissue in the cortex within 350 μ m of the implant was evident after 12 weeks of load application. Marginal bone resorption may also be related to the lack of mechanical coupling between the machined coronal region of the implant and the bone, which prevents effective transfer of occlusal forces from the implant to the cortical bone. The extremely low intraosseous strain (\geq below 100 microstrain) thus causes bone resorption due to disuse atrophy.^{17,18} If the surface of the implant is rough, the total area used to transfer occlusal forces to the bone increases. Eventually, lower stress and strain can be achieved in the vicinity of the implant. Rough surface implants also provide better mechanical interlock with the bone than machined-surface implants do.¹⁹

The type of prosthesis affects the mode of implant loading. In cement-retained implant restorations, the occlusal surface is devoid of screw holes and the occlusion can be developed that responds to the need for axial loading. Screw-retained fixed prosthesis or overdentures, however, are subjected to off-set loads that cause a substantial increase in bending moments.²⁰

Mericske-Stern and collaborators²³ also registered forces on implants supporting one-piece full-arch fixed prosthesis and bar-retained overdentures in the maxilla. They concluded that, the type of prosthesis did not have a determining effect

on the force pattern. However, in overdenture treatments, the resorption pattern of the maxilla affects positioning of the implants and the denture teeth. Since the positioning of denture teeth frequently creates an anterior or labial cantilever, which acts as a long lever-arm, high bending moments are created on maxillary implants. This situation may explain why implant survival rates are significantly lower in the maxilla, particularly with overdenture treatments.^{22,23}

Regardless of the design, the occlusal materials for implant-prosthesis complexes have been a topic of research interest in recent studies. Skalak²⁴ envisaged that the use of acrylic resin teeth would be useful for shock protection on implants and Brånemark and co-workers² have also recommended the use of acrylic resin as the material of choice for the occlusal surfaces of implant-retained prostheses. The resiliency of this material was suggested as a safeguard against the negative effects of impact forces and microfractures at the bone-implant interface. The literature, however, is inconclusive on its effect on shock absorption.²⁵⁻²⁹ In fact, acrylic resins seem to prevent technical problems and subjective disadvantages. For example, due to their low wear resistances, premature contacts often occur after several months of prosthesis delivery. On the other hand, gold and porcelain surfaces are believed not to provide force absorption, but they are also frequently used. Although the choice of prosthesis material still remains as a topic of controversy and argument, there is a consensus that it does not have any influence on implant survival.³⁰

When dealing with a complex stress analysis problem in which a complete theoretical solution may prove impractical with respect to time, cost, or degree of difficulty, experimental techniques are often used. Current techniques employed to evaluate the biomechanical loads on implants comprise the use of mathematical calculations, photoelastic stress analysis, two or three-dimensional finite element stress analysis and strain-gauge analysis (SGA). The application of SGA on dental implants is based on the use of electrical resistance strain-gauges and its associated equipment, and provides both *in-vivo* and *in-vitro* measurement of strain under static or dynamic loads. Under an applied force, a strain gauge measures the mean dimensional change where it is bonded or embedded. For *in-vivo* or *in-vitro* strain-gauge experimentation, however, this may not be provided due to several factors included in force transmission during load application by the opposing teeth or by an apparatus. The placement of the gauges may have slight inaccuracies, or the angulation of implants may not be as precise as in a theoretical model. Overall, the very nature of the physical experimental technique makes it inherently subject to random errors. Currently, although SGA is the only technique that allows *in-vivo* measurements during clinical loading, the results of *in-vivo* and *in-vitro* SGA do not agree on the quantification of bending moments.^{31,32}

Correct qualification and quantification of forces on implants

are crucial for understanding the biomechanics of implants. Biomechanical studies should, therefore, be designed not only for descriptive purposes but also for obtaining reliable and accurate data that have clinical relevance.

The purpose of this study is to investigate the strain of implants using chewing simulator (MTS 858 Mini Bionix II systems, MTS systems corp., Minn, USA) combined with strain gauge in mandibular implant-supported fixed prostheses under various dynamic loads and to evaluate and compare the quantity and distribution of mean strain values on the working and non-working sides of implant-supported fixed prostheses.

MATERIALS AND METHODS

1. Fabrication of measurement model

A partially edentulous mandibular acrylic resin model and opposing teeth were fabricated with auto-polymerizing resin (POLYUROCK; Metalor technologies, Stuttgart, Swiss) and artificial denture teeth (Endura; Shofu inc., Kyoto, Japan). This auto-polymerizing resin has a flexural modulus of 3,000 MPa; similar to that of the mandibular trabecular bone.³³ The areas from the mandibular canine to the second molar were specially designed to be the missing span for the installation of implants and screw-retained fixed prostheses.

The interarch distance from the alveolar ridge of mandibular missing span to the cusp of opposing teeth was endowed at least with 12 mm-apart, because strain gauges and the abutment complex need sufficient vertical space (> 5 mm). After fabrication of implant surgical stent, six dental implants, ϕ 4.0 mm \times 11.5 mm height (US II; Osstem, Seoul, Korea), were installed at the mandibular canine (Fx1, Fx4), the second premolar (Fx2, Fx5) and the second molar (Fx3, Fx6) areas in the missing spans by using standard surgical procedures in real clinical situations. And then, six dental implants were endowed with 30 N torque value of initial stability by using an electric torque measuring device. All extended vertical axes of the six implants were headed for functional cusps of the opposing teeth, so that screw holes of screw-retained implant prostheses could be positioned centrally.

2. Fabrication of implant-supported fixed prostheses

Three implant-supported 5-unit screw-retained fixed prostheses were made by using standard methods of superstructure fabrication. The entire procedure, including impression taking, master cast fabrication, wax-up, casting, and finishing, was carried out in accordance with recommended protocols.^{34,35} The fixture-level impression was taken using an individual resin tray and pick-up type impression copings with polyvinyl-siloxane impression material (Imprint II; 3M ESPE, MN., USA).

The master cast was fabricated with stone and implant lab analogues. And then, standard abutments (ϕ 4.5 mm \times 5.5 mm height, Osstem, Seoul, Korea) were connected to lab analogues. The mandibular cast and the opposing maxillary cast were mounted arbitrarily on a semi-adjustable articulator. The condylar and anterior guidances of the articulator were set at 30 degrees and the Bennett angle was set at 15 degrees.

After the wax-up procedure, gold frameworks were cast with Type III gold alloy (Harmony C&B55; Ivoclar-vivadent, Liechtenstein, Germany) and recommended protocols were performed to obtain a passive fit of the superstructures.

Reinforced hard resin (Tescera; Ivoclar-vivadent, Liechtenstein, Germany) was selected as the material for the occlusal table because it is favorable to transfer force and easy to add or eliminate, allowing application of different occlusion types. The occlusal table was designed to have more than three occlusal contacts on the functional cusp, central fossa and marginal ridge of each tooth.

3. Endowment with three different occlusion types

To minimize errors, by addition or elimination of Tescera materials, three test groups of implant-supported 5-unit fixed prostheses with different occlusion types were fabricated on the same supra-structure. The following are three different groups with different occlusion types of implant-supported fixed prostheses.

- Group I: Canine protected occlusion
- Group II: Unilaterally balanced occlusion
- Group III: Bilaterally balanced occlusion

4. Attachment of strain gauges and equipment set-up

The surfaces of six standard abutments were roughened by sandblasting media and marked with a felt-tipped pen bucco-lingually. Two strain gauges (KFG-1-120-C1-11L1M2R; KYOWA electronic instruments, Tokyo, Japan) were then attached with adhesive (M-bond 200; Tokuyama, Tokyo, Japan) bucco-lingually on each standard abutment (Fig. 1). A total of twelve strain gauges (Ch1 - Ch6 in working side, the other six Ch7 - Ch12 in non-working side) were attached on test model and connected to dynamic signal conditioning strain amplifiers (CTA1000, Curiotech inc., Paju, Korea). The amplified dynamic strain signals were monitored with a software program (DA1700, National Instrument., TX, USA).

5. Control loading and monitoring dynamic strain signals

The mandibular test models with different occlusion types and the opposing teeth models were mounted on a MTS chewing simulator (MTS 858 Mini Bionix II systems, MTS sys-

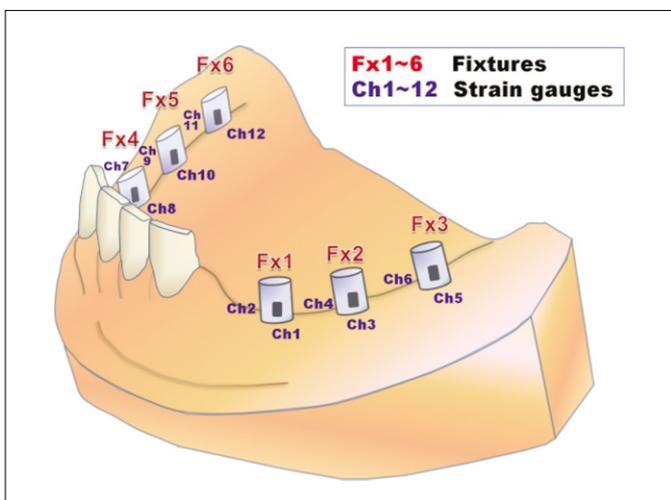


Fig. 1. Graphic illustration of the measurement model and strain gauges.

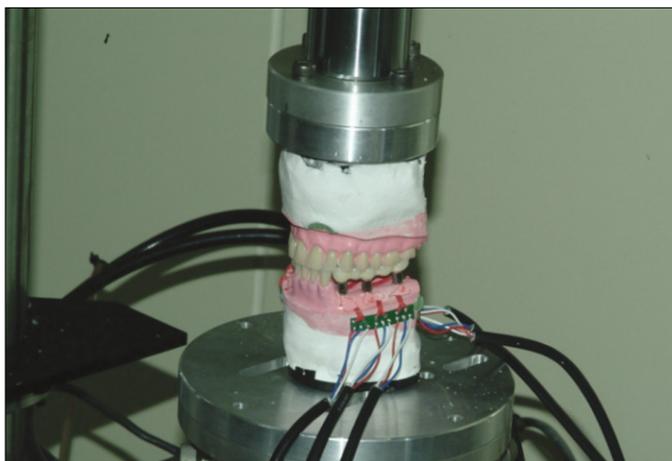


Fig. 2. The overview of test model mounted on MTS machine.

tems corp., MN, USA) using a custom-made positioning jig. Then, six channels of strain gauges on the mandibular working side were connected to dynamic signal conditioning strain amplifiers and a zero point calibration was performed (Fig. 2). The programmed vertical and lateral combined dynamic loads, 0 - 300 N in 25 N increments, were applied on the mandibular test model twenty-five times, and ten stable dynamic strain signals were monitored and recorded. After monitoring the signals on the working side, the same experiments were repeated for the other six channels on the non-working side. Figure 3 shows the profile curve of the dynamic load controlled by MTS chewing simulation function. The blue line represents the quantity and distribution of the vertical axial load, and the red line those of the concurrent lateral shear strength.

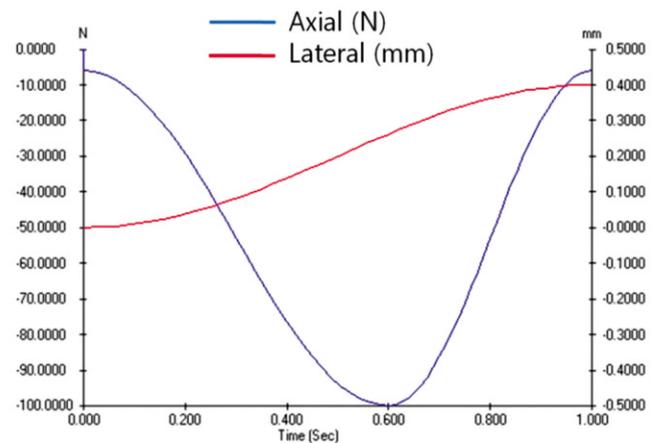


Fig. 3. The controlled profile curve of dynamic load.

6. Statistical analysis

First, strain values of the working side of each group under different dynamic loads were compared with those of the non-working side using the paired sample t-test. Second, multiple comparisons of three implants positioned on the working side in each group were performed using the one-way ANOVA with the Tukey HSD (Honestly Significant Difference) multiple comparison method. Last, multiple comparisons of the results from the working and non-working sides in the three groups were also performed using the same methods.

RESULTS

1. The mean strain value of the implants in different groups

An example of curves of strain on working side of Group I under 100 N dynamic load were drawn in complex shapes, as in figure 4. The strain values of the buccally positioned Ch1, 3, and 5 strain gauges of the working side and those of the lingually positioned Ch8, 10 and 12 strain gauges in each group represent (+) tensile strain values. On the other hand, the values of the lingually positioned Ch2, 4 and 6 strain gauges of the working side and those of the buccally positioned Ch7, 9, and 11 strain gauges in each group represent (-) compressive strain values.

The arithmetical absolute mean value of two strain gauges attached to each implant fixture was calculated. Table 1, 2, and 3 show the mean absolute strain value of each implant fixture, and Figure 5, 6 and 7 show the curves of strain values under increasing dynamic loads from 25 N to 300 N.

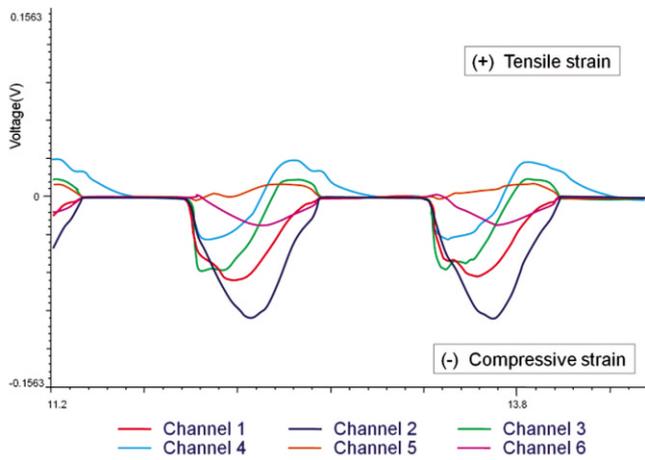


Fig. 4. An example of curves of strain on working side of Group I under 100 N dynamic load.

Table 1. The mean absolute strain value for the six implants of Group I

| Load | Mean absolute strain ($\mu\epsilon$) | | | | | |
|-------|--|--------|--------|------------------|--------|-------|
| | Working side | | | Non-working side | | |
| | Fx1 | Fx2 | Fx3 | Fx4 | Fx5 | Fx6 |
| 25 N | 61.80 | 22.45 | 28.70 | 12.00 | 14.10 | 14.15 |
| 50 N | 72.70 | 31.45 | 34.30 | 20.00 | 17.95 | 17.15 |
| 75 N | 90.35 | 42.60 | 41.75 | 33.25 | 22.75 | 20.10 |
| 100 N | 113.35 | 60.55 | 52.70 | 47.10 | 31.60 | 23.95 |
| 125 N | 140.80 | 73.95 | 62.65 | 58.95 | 39.60 | 30.30 |
| 150 N | 179.20 | 105.00 | 78.30 | 73.35 | 50.35 | 40.15 |
| 175 N | 245.95 | 148.70 | 105.20 | 85.85 | 62.00 | 48.80 |
| 200 N | 307.45 | 185.00 | 134.45 | 95.70 | 73.70 | 57.55 |
| 225 N | 326.75 | 201.45 | 146.65 | 101.75 | 83.25 | 63.70 |
| 250 N | 351.50 | 227.40 | 156.10 | 108.40 | 92.00 | 70.05 |
| 275 N | 369.90 | 261.60 | 169.30 | 113.10 | 96.20 | 78.05 |
| 300 N | 382.05 | 272.95 | 180.90 | 118.10 | 100.65 | 82.70 |

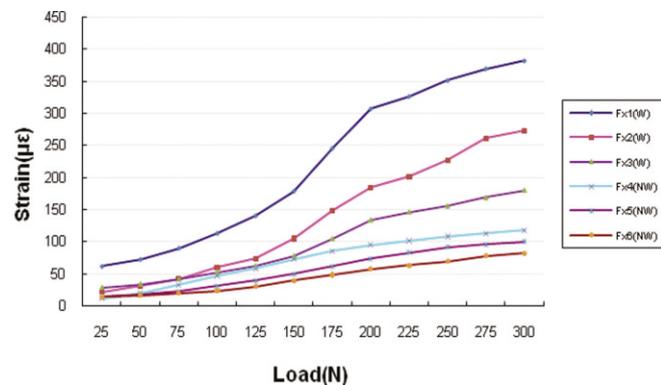


Fig. 5. The mean absolute strain value for the six implants of Group I.

Table 2. The mean absolute strain value for the six implants of Group II

| Load | Mean absolute strain ($\mu\epsilon$) | | | | | |
|-------|--|--------|--------|------------------|--------|--------|
| | Working side | | | Non-working side | | |
| | Fx1 | Fx2 | Fx3 | Fx4 | Fx5 | Fx6 |
| 25 N | 16.15 | 18.10 | 17.80 | 22.80 | 33.25 | 11.05 |
| 50 N | 27.35 | 40.80 | 37.10 | 31.85 | 41.20 | 20.80 |
| 75 N | 47.20 | 80.20 | 58.95 | 44.75 | 49.70 | 28.85 |
| 100 N | 64.25 | 143.60 | 87.70 | 55.20 | 67.95 | 42.65 |
| 125 N | 77.10 | 189.85 | 125.95 | 51.20 | 80.85 | 61.30 |
| 150 N | 90.90 | 227.90 | 157.75 | 65.50 | 95.55 | 75.25 |
| 175 N | 109.20 | 261.20 | 179.40 | 72.85 | 103.50 | 83.55 |
| 200 N | 130.60 | 313.35 | 205.40 | 78.55 | 108.10 | 88.20 |
| 225 N | 150.70 | 347.40 | 261.25 | 81.75 | 110.80 | 91.70 |
| 250 N | 180.15 | 392.05 | 311.95 | 84.70 | 115.75 | 95.65 |
| 275 N | 189.25 | 438.10 | 352.30 | 88.70 | 118.65 | 99.55 |
| 300 N | 199.50 | 451.05 | 362.85 | 90.70 | 120.70 | 102.05 |

Table 3. The mean absolute strain value for the six implants of Group III

| Load | Mean absolute strain ($\mu\epsilon$) | | | | | |
|-------|--|--------|--------|------------------|--------|--------|
| | Working side | | | Non-working side | | |
| | Fx1 | Fx2 | Fx3 | Fx4 | Fx5 | Fx6 |
| 25 N | 52.05 | 55.50 | 27.40 | 39.20 | 73.75 | 73.75 |
| 50 N | 69.95 | 78.65 | 44.25 | 40.25 | 77.90 | 83.35 |
| 75 N | 80.30 | 99.75 | 62.30 | 43.95 | 91.10 | 93.00 |
| 100 N | 94.35 | 119.90 | 78.65 | 48.45 | 101.10 | 103.15 |
| 125 N | 108.20 | 140.80 | 94.90 | 53.25 | 110.90 | 119.55 |
| 150 N | 116.50 | 157.30 | 106.90 | 54.80 | 116.25 | 123.35 |
| 175 N | 129.50 | 176.75 | 119.45 | 55.75 | 120.10 | 133.95 |
| 200 N | 138.20 | 199.00 | 130.90 | 57.80 | 128.40 | 146.55 |
| 225 N | 148.20 | 208.55 | 139.95 | 59.10 | 131.45 | 153.75 |
| 250 N | 161.50 | 235.60 | 152.45 | 60.55 | 136.95 | 162.75 |
| 275 N | 169.50 | 246.85 | 160.30 | 61.30 | 142.70 | 174.15 |
| 300 N | 176.75 | 267.05 | 170.40 | 61.50 | 146.60 | 181.15 |

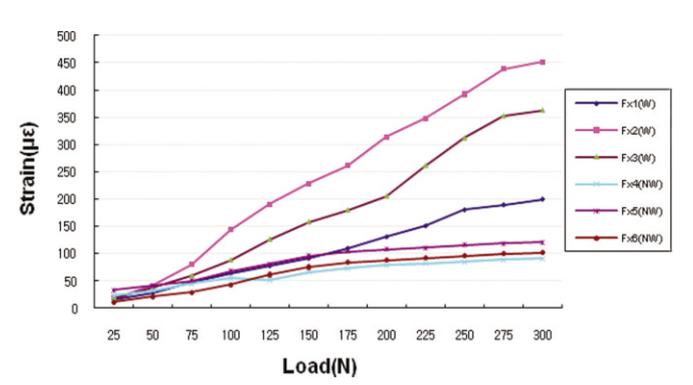


Fig. 6. The mean absolute strain value for the six implants of Group II.

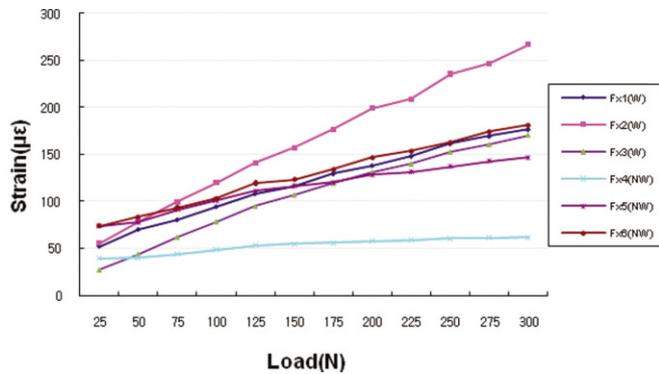


Fig. 7. The mean absolute strain value for the six implants of Group III.

2. Comparative analysis of the working side with the non-working side

In order to compare the mean strain values of the working side with those of the non-working side in each group, paired sample t-tests were carried out. In Group I, there was a significant difference between the mean strain value of working side and that of the non-working side with a t-value of 7.58. In Group II, the same was observed with a t-value of 6.25. In Group III, however, a much smaller t-value (3.83) was observed, showing a difference not as significant as observed in Group I or Group II (Table 4).

Table 4. The paired sample t-tests of working side Vs non-working side in each group

| | Paired difference | | | |
|------------------|-------------------|-------|-------------------|------|
| | Mean | SD | Stand. Error Mean | t |
| Group I (W-Nw) | 93.54 | 74.09 | 12.34 | 7.58 |
| Group II (W-Nw) | 103.59 | 99.48 | 16.58 | 6.25 |
| Group III (W-Nw) | 32.14 | 50.39 | 8.39 | 3.83 |

3. Multiple comparisons of three implants positioned on the working side

In order to compare the mean strain values of the three implants positioned on the working side (Fx1, 2, and 3) of each group statistically, multiple comparisons were made using the Tukey's HSD (Honestly Significant Difference) methods (Table 5). In the case of Group I, the three P values (significance probabilities) between the groups are below .05, so any one of the three mean strain values may be significantly different from the others, with a 95% confidence interval. And the P-value of Fx2 - Fx3 is 0.039, which is higher than the others (P < .01), it means that the statistical difference is comparatively lower than those of Fx1 - Fx2 or Fx1 - Fx3. In the case of Group II, the same trend was observed as in Group I: the three P values of between the groups are below 0.01.

In the last case of Group III, the P-values of Fx1 - Fx2 and Fx2 - Fx3 are below .05. But the P-value of Fx1 - Fx3 is 0.103 (P > .05). Therefore, the mean strain value of Fx1 was not different from that of Fx3 with a 95% confidence interval.

Table 5. The multiple comparisons of the three implants positioned on working side

| | (I) Fixture | (J) Fixture | Mean difference (I-J) | Std. error | Sig.(P) | |
|-----------|-------------|-------------|-----------------------|------------|----------|-------------------------------------|
| Group I | Fx1 | Fx2 | 84.06 | 13.98 | < 0.01** | The canine area > |
| | | Fx3 | 120.90 | 13.98 | < 0.01** | The 2 nd premolar area > |
| | Fx2 | Fx1 | -84.06 | 13.98 | < 0.01** | The 2 nd molar area |
| | | Fx3 | 36.84 | 13.98 | < 0.05* | |
| | Fx3 | Fx1 | -120.90 | 13.98 | < 0.01** | |
| | | Fx2 | -36.84 | 13.98 | < 0.05* | |
| Group II | Fx1 | Fx2 | -135.10 | 18.53 | < 0.01** | The 2 nd premolar area > |
| | | Fx3 | -73.00 | 18.53 | < 0.01** | The 2 nd molar area > |
| | Fx2 | Fx1 | 135.10 | 18.53 | < 0.01** | The canine area |
| | | Fx3 | 62.10 | 18.53 | < 0.01** | |
| | Fx3 | Fx1 | 73.00 | 18.53 | < 0.01** | |
| | | Fx2 | -62.10 | 18.53 | < 0.01** | |
| Group III | Fx1 | Fx2 | -45.06 | 6.09 | < 0.01** | The 2 nd premolar area > |
| | | Fx3 | 13.10 | 6.09 | > 0.05 | The 2 nd molar area ≐ |
| | Fx2 | Fx1 | 45.06 | 6.09 | < 0.01** | The canine area |
| | | Fx3 | 58.15 | 6.09 | < 0.01** | |
| | Fx3 | Fx1 | -13.10 | 6.09 | > 0.05 | |
| | | Fx2 | -58.15 | 6.09 | < 0.01** | |

Tukey HSD (Honestly Significant Difference), * The P value is significant at the 0.05 level, ** The P value is significant at the 0.01 level.

Table 6. The multiple comparisons of the mean strain values for the working or non-working side

| | (I) Group | (J) Group | Mean difference (I-J) | Std. error | Sig. (P) | |
|------------------|-----------|-----------|-----------------------|------------|----------|---|
| Working side | I | II | -24.40 | 14.71 | > 0.05 | Uni. balanced occlusion type was significantly larger than the others |
| | | III | 20.76 | 14.71 | > 0.05 | |
| | II | I | 24.40 | 14.71 | > 0.05 | |
| | | III | 45.16 | 14.71 | < 0.01** | |
| | II | I | -20.76 | 14.71 | > 0.05 | |
| | | II | -45.16 | 14.71 | < 0.01** | |
| Non-working side | I | II | -14.36 | 5.75 | < 0.05* | Bi. balanced occlusion type was significantly larger than the others |
| | | III | -40.64 | 5.75 | < 0.01** | |
| | II | I | 14.36 | 5.75 | < 0.05* | |
| | | III | -26.29 | 5.75 | < 0.01** | |
| | III | I | 40.64 | 5.75 | < 0.01** | |
| | | II | 26.29 | 5.75 | < 0.01** | |

Tukey HSD (Honestly Significant Difference), * The *P* value is significant at the 0.05 level, ** The *P* value is significant at the 0.01 level.

4. Multiple comparisons of the mean strain values for the working or non-working side

At last, in order to compare the generalized mean strain values for the working or non-working side of the three groups, multiple comparisons were made using the Tukey's HSD methods, too.

The generalized mean strain values for the working side of Group I, Group II, and Group III were 151.83 $\mu\epsilon$, 176.23 $\mu\epsilon$, and 131.07 $\mu\epsilon$, respectively. There was no significant difference between Group I and Group II or between Group I and Group III with a 95% confidence interval ($P > .05$). But there was a significant difference between Group II and III ($P < .05$, Table 6).

The generalized mean strain values of non-working side of Group I, Group II, and Group III were 58.29 $\mu\epsilon$, 72.64 $\mu\epsilon$, and 98.93 $\mu\epsilon$, respectively. There were significant differences between any two among the three groups ($P < .05$, Table 6).

DISCUSSION

Curtis *et al.*³⁶ reported that partial edentulous mandibles were more common than partial edentulous maxillae and the class I mandibular RPDs were the most common type for either dental arch and the percentage of Kennedy class I RPDs were 40%, class II 33%, class III 18%, and class IV were 9%. In this study, the reason for choosing the mandibular class I partial edentulous test model was that we had often been faced with this clinical situation. When anterior fixed ceramic restoration and bilateral posterior implant-supported fixed prostheses are combined, we should take occlusion-related factors into special considerations because the treatment would be mandibular full-mouth rehabilitation.

This study have realized *in-vitro* chewing simulations using the dynamic load control of the MTS machine and, it was the

latest mechanical study of the implant-abutment complex on strain under various dynamic loads using the combined method of the MTS chewing simulation and strain gauge. So this technique will be a good methodological way for any other study of implant on strain under various dynamic loads containing lateral forces.

The methodological key point of this study was to produce three occlusion types on implant-supported fixed prostheses with inclined cusp angle and anterior guidance with pre-determined mandibular condylar guidance. But the MTS machine was able to reproduce sufficiently the three dimensional movements of the real mandible.

For dentate humans, the maximum biting force varies among individuals and in different regions of the dental arch.^{37,38} The greatest maximum biting force reported to date is 443 kgN.³⁹ Dentate patients have 5 - 6 times higher bite force than complete denture wearers.⁴⁰ Present evidence based principally on static force measurements indicates that the average biting force is 100 - 150 N in adult males, and males have a higher biting force than females.³⁷ Patients with implant-supported fixed prosthesis have a masticatory muscle function equal to or approaching that of patients with natural teeth or with tooth-supported fixed partial dentures.⁴¹ For this reason, the dynamic load of the MTS machine was set in the range of +25 N to +300 N in 25 N increments to include light chewing forces to maximal. A careful notice of position of strain gauge and data analysis was taken not to exaggerate error. To minimize errors in data analysis generated by incorrect position of the strain gauge, two strain gauges were attached to the abutment on both the buccal and the lingual side, and then the arithmetical absolute mean value was calculated.

The mean strain values of each group under the same mechanical conditions, except for the occlusion type, had different distributions and quantities depending on the implant position and the magnitude of the dynamic load. These data were

analyzed by statistical methods to yield the following results.

First, the paired sample t-tests on the working side versus the non-working side of each group showed that the t-values of Group I and II were approximately twice that of Group III. This proved statistically that the mean strain values of the working side were significantly different from those of the non-working side in Group I and Group II but not in Group III. In other words, only bilaterally balanced occlusion type dispersed the occlusal loads evenly and a comparatively smaller strain was generated under the same dynamic load.

Multiple comparisons of the mean strain value for three implants positioned on the working side of Group I showed that the mean strain values were 220.15 $\mu\epsilon$, 136.09 $\mu\epsilon$, and 99.25 $\mu\epsilon$ for Fx1, Fx2, and Fx3, respectively, and proved that any one was significantly different from the others with a 95% confidence interval ($P < .05$). This suggested that strain was mainly concentrated on an area of the working side canine and much more stress would be generated around the Fx1-abutment complex.

In Group II, multiple comparisons showed that the mean strain values were 241.97 $\mu\epsilon$, 179.87 $\mu\epsilon$, and 106.86 $\mu\epsilon$ for Fx2, Fx3, and Fx1, respectively, and proved that any one was significantly different from the others with a 95% confidence interval ($P < .05$). This suggested that strain was mainly concentrated on an area of working side second premolar and much more stress would be generated around the Fx2-abutment complex. Mericske-Stern and Zarb⁴² investigated occlusal forces in a group of partially edentulous patients restored with ITIw implants supporting fixed partial prostheses and measured an average value of maximum occlusal force lower than 200 N in the first premolars and molars and 300 N in the second premolars. These data suggest that forces on implants are dependent on the location of the implant in the dental arch and implants placed in the posterior region of the mouth are at greater risk of overloading.

In Group III, multiple comparisons showed that the mean strain values were 165.48 $\mu\epsilon$, 120.42 $\mu\epsilon$, and 107.32 $\mu\epsilon$ for Fx2, Fx3, and Fx1, respectively, and proved that there was no significant difference between Fx1 and Fx3 with a 95% confidence interval ($P > .05$). Unexpectedly, however, the mean strain value of Fx2 was significantly different from the others ($P < .05$). But, it is difficult to give this finding some significance because bilaterally balanced occlusion type disperses strain to all implants evenly.

Multiple comparisons of the generalized mean strain values for the working sides of the three groups showed that the mean strain values were 151.83 $\mu\epsilon$, 176.23 $\mu\epsilon$, and 131.07 $\mu\epsilon$ for Group I, Group II, and Group III, respectively. There was a significant difference between Group II and Group III ($P < .05$), but the mean strain value for the working side of Group I was not significantly different from the others with a 95 % confidence interval ($P > .05$). This means that only unilaterally

ally balanced occlusion has more remarkable strain on the working side than the bilaterally balanced occlusion.

Lastly, multiple comparisons of the generalized mean strain values for non-working side of the three groups showed that the mean strain values were 58.29 $\mu\epsilon$, 72.64 $\mu\epsilon$, and 98.93 $\mu\epsilon$ for Group I, Group II, and Group III, respectively. That of bilaterally balanced occlusion was significantly different from the others with a 95% confidence interval ($P < .05$).

These statistical analyses suggest that the strain of implants under dynamic load was related to the position of the implants in the dental arch and also to the occlusion type including the cusp inclination, the condylar guidance, and the anterior guidance.

CONCLUSION

In this study, strain gauge analyses using the MTS machine were carried out to evaluate the quantity and distribution of strain generated from three implant supported 5-unit fixed implant prostheses under dynamic load. The following conclusions were drawn.

1. The mean strain values for the working side of Groups I and II were significantly different from that for the non-working side ($t = 6.2 - 7.5$). But, Group III ($t = 3.8$) was not.
2. The comparative sequence of the mean strain values for the three implants of Group I working side was Fx1 > Fx2 > Fx3; one was significantly different from the others ($P < .05$).
3. The comparative sequence of the mean strain values for the three implants of Group II working side was Fx2 > Fx3 > Fx1; one was significantly different from the others ($P < .01$).
4. The comparative sequence of the mean strain values for the three implants of Group III working side was Fx2 > Fx3 \approx Fx1; there was no significant difference between Fx1 and Fx3 ($P > .05$).
5. Multiple comparisons of the generalized mean strain values for the working side of the three groups showed that only the value of Group II was significantly larger than that of Group III ($P < .01$).
6. Multiple comparisons of the generalized mean strain values for the non-working side of the three groups showed that the value of Group III was significantly larger than those of Group I or Group II ($P < .01$).

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