

# Axial Loads on Implant-Supported Partial Fixed Prosthesis for External and Internal Hex Connections and Machined and Plastic Copings: Strain Gauge Analysis

Luis Gustavo Oliveira de Vasconcellos, DDS, MS, PhD<sup>1\*</sup>  
 Alberto Noriyuki Kojima, DDS, MS, PhD<sup>1</sup>  
 Renato Sussumu Nishioka, DDS, MS, PhD<sup>1</sup>  
 Luana Marotta Reis de Vasconcellos, DDS, MS, PhD<sup>2</sup>  
 Ivan Balducci, Eng, MSc<sup>3</sup>

The aim of this *in vitro* study was to use strain gauge (SG) analysis to compare the effects of the implant-abutment joint, the coping, and the location of load on strain distribution in the bone around implants supporting 3-unit fixed partial prostheses. Three external hexagon (EH) implants and 3 internal hexagon (IH) implants were inserted into 2 polyurethane blocks. Microunit abutments were screwed onto their respective implant groups. Machined cobalt-chromium copings and plastic copings were screwed onto the abutments, which received standard wax patterns. The wax patterns were cast in a cobalt-chromium alloy ( $n = 5$ ): group 1 = EH/machined, group 2 = EH/plastic, group 3 = IH/machined, and group 4 = IH/plastic. Four SGs were bonded onto the surface of the block tangentially to the implants. Each metallic structure was screwed onto the abutments and an axial load of 30 kg was applied at 5 predetermined points. The magnitude of microstrain on each SG was recorded in units of microstrain ( $\mu\epsilon$ ). The data were analyzed using 3-factor repeated measures analysis of variance and a Tukey test ( $\alpha = 0.05$ ). The results showed statistically significant differences for the type of implant-abutment joint, loading point, and interaction at the implant-abutment joint/loading point. The IH connection showed higher microstrain values than the EH connection. It was concluded that the type of coping did not interfere in the magnitude of microstrain, but the implant/abutment joint and axial loading location influenced this magnitude.

**Key Words:** *biomechanics, dental implants, dental prosthesis, implant-supported dental prosthesis*

## INTRODUCTION

Occlusal overload has been given as the primary factor for peri-implant bone loss, loss of implants, and loss of implant-supported prostheses.<sup>1,2</sup> Occlusal loads are first introduced to the prosthesis and are delivered to the bone/implant interface;<sup>3</sup> hence, the development and maintenance of the bone/implant interface are particularly dependent on the control of biomechanical loads. Bones carrying mechanical loads adapt their strength to the load applied on them by bone modeling/remodeling. The response to increased mechanical stress below a certain threshold will be a strengthening of the bone by increasing the bone density or apposition of bone. On the other hand,

fatigue micro-damage resulting in bone resorption may be the result of mechanical stress beyond this threshold.<sup>2,4,5</sup>

Once practitioners developed techniques to successfully treat completely edentulous jaws, they attempted to use those techniques to restore a partially edentulous jaw. However, this clinical application presents distinct challenges for both surgical and prosthetic teams. Compared with implant-supported total fixed prostheses, implant-supported partial fixed prostheses are more susceptible to the bending moment generated by occlusal loads because they lack the benefit of cross-arch stabilization.<sup>6</sup> Moreover, the posterior region of the oral cavity presents higher occlusal loading and lower bone quality than the anterior region; additionally, bone height is limited by the maxillary sinus or the mandibular nerve.

In a retrospective clinical analysis of the relation between the fracture of implants and occlusal overload, Rangert et al<sup>6</sup> found that 90% of implant fractures occurred in the posterior segment, supported by one or more implants, in association with cantilever, bruxism, or high occlusal loads. In a systematic review, Pjetursson et al<sup>7</sup> assessed the 5- and 10-year survival of implant-supported fixed partial dentures and described the incidence of biological and technical complications. After 5 years, the cumulative incidence of connection-related complications (screw loosening or fracture) was 7.3% and 14% for

<sup>1</sup> Department of Dental Materials and Prosthodontics, School of Dentistry of São José dos Campos, São Paulo State University, São José dos Campos, Brazil.

<sup>2</sup> Department of Bioscience and Buccal Diagnosis, School of Dentistry of São José dos Campos, São Paulo State University, São José dos Campos, Brazil.

<sup>3</sup> Department of Community Dentistry and Pediatric Clinic, São José dos Campos Dental School, São Paulo State University, São José dos Campos, Brazil.

\* Corresponding author, e-mail: luis.vasconcellos@fosjc.unesp.br  
 DOI: 10.1563/AAID-JOI-D-10-00174

superstructure-related complications (veneer and framework fracture).

Several types of abutment connection designs, such as external hexagons (EHs) and internal hexagons (IHs), have been used clinically. The resorption of bone in the vicinity of the fixture occurs to a certain level in all implant systems. The amount of marginal bone loss around EH connections and internal cone connections is almost the same.<sup>8</sup> Although mechanical, clinical, and microbiological advantages and disadvantages have been indicated for external and internal systems, the biomechanical influences around implants after loading have yet to be closely examined.

Recent studies have investigated the stresses caused by implant-supported prosthesis fabrication methods by varying the type of coping.<sup>9-12</sup> However, these studies observed stresses only during the fixation of implant-supported fixed partial protheses.

The aim of this *in vitro* study was to use strain gauge (SG) analysis to compare the effects of the implant-abutment joint, the coping, and the location of load on strain distribution in the bone around the implants supporting 3-unit fixed partial protheses.

## MATERIALS AND METHODS

### Preparation of the test specimens

To simulate real-life clinical conditions, 3 EH implants (Master Screw, 3.75-mm diameter, 13-mm depth; Conexão Sistemas de Prótese, Arujá, Brazil) and 3 IH implants (Conect AR, 3.75-mm diameter, 13-mm depth; Conexão Sistemas de Prótese) from mesial to distal, labeled 1, 2, and 3, were arranged in the middle of 2 measurement models consisting of a 70 × 40 × 30 mm<sup>3</sup> rectangular polyurethane block (Polyurethane F16; Axson, Cergy, France) with known mechanical properties (Young's modulus of 3.6 GPa). One matrix that could generate a constant implant placement was custom-built. The implants were inserted in a straight line into the polyurethane block. The distance between the centers of the implants was set at 7 mm, leaving sufficient space for the SG. Microunit abutments (Conexão Sistemas de Prótese) were screwed onto the respective implants with a 20 Ncm torque using the implant manufacturer's manual torque driver (Conexão Sistemas de Prótese).

### Fabrication of metallic superstructures

Each specific polyurethane block served as the base for wax-up procedures. The patterns were fabricated using a pattern resin (GC Pattern Resin; GC Europe NV, Leuven, Belgium) and wax (Kronen wachs; Bego Bremer Goldschalgeri, Bremen, Germany). Wax patterns made of 2 different prosthetic copings, machined cobalt-chromium coping (Conexão Sistemas de Prótese) and plastic copings (Conexão Sistemas de Prótese), were used in the study. Prosthetic copings were attached to the abutment, then the wax-up was adapted under slight finger pressure on the polyurethane blocks to eliminate the inevitable dimensional changes originating from impression procedures (Figure 1).<sup>9</sup>

The wax patterns were sprued, invested, and one-piece cast in an induction oven with cobalt-chromium alloy (Wirobond SG, Bego Bremer Goldschalgeri). To avoid bias resulting from manufacturing conditions, random sets comprising frameworks of different types were put together and cast. The castings were cleaned, finished, and polished, and care was taken not to damage the internal surface of the copings, whose interiors were inspected under a binocular microscope to check for casting imperfections. The abutments received 3-unit superstructures. The fit and passivity of the superstructures were checked without torque tightening. The superstructures showed satisfactory adaptation, which was confirmed by direct vision in conjunction with tactile sensation through an explorer.<sup>13</sup> Superstructures showing signs of instability were excluded, and a new one was cast.

Each metallic superstructure was numbered and labeled according to its corresponding group. The total sample constituted 20 superstructures distributed randomly and equally among the EH and IH groups. These were differentiated by casting of machined and plastic copings.

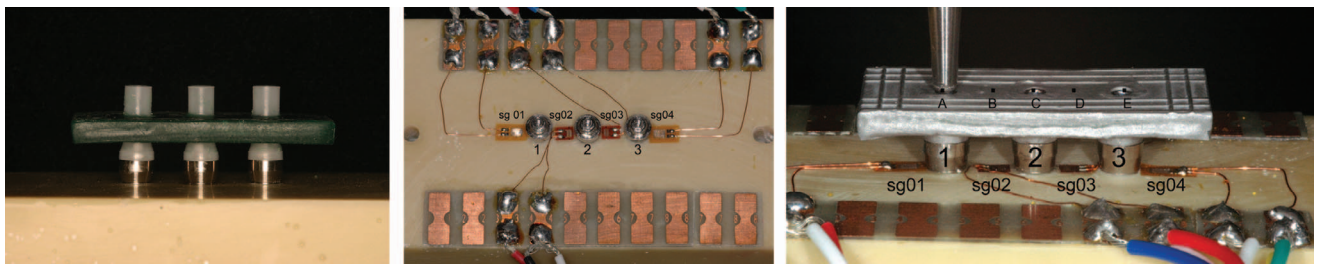
### SG analysis

Four SGs (KFG-02-120-c1-11N30C2; Kyowa Electronic Instruments Co, Ltd, Tokyo, Japan) were bonded onto the surface of each polyurethane block using a thin film of methyl-2-cyanoacrylate adhesive (M-Bond 200; Vishay Measurements Group, Raleigh, NC): SG 1 was placed mesially adjacent to implant 1; SG 2 and SG 3 were placed mesially and distally adjacent to implant 2, respectively; and SG 4 was placed distally adjacent to implant 3 (Figure 2). Each gauge was wired separately, and the 4 SGs were arranged in series to form a full Wheatstone bridge. The leads from the SGs were connected to a multichannel bridge amplifier to form one leg of the bridge. A computer (Intel 775P Pentium 4 Q6600, Dell Computadores do Brasil Ltda, Eldorado do Sul, RS, Brazil) was interfaced with the bridge amplifier to record the output signal of polyurethane surface. A data acquisition system software (System 5000 Model 5100B; Vishay Measurements Group, Raleigh, NC) was used to record the data.

The occlusal screws of the superstructure were tightened onto the Microunit abutments with a hand-operated screwdriver until the screws started to engage, based on tactile sensation, while applying a torque of 10 Ncm using the manufacturer's manual torque-controlling device.

Five loading points were selected to apply a static vertical load on the metallic superstructures. Point A was located on the hole of the retention screw of implant 1, point B was located centrally between the holes of the retention screws of implants 1 and 2, point C was located on the hole of the retention screw of implant 2, point D was located centrally between the hole of the retention screws of implants 2 and 3, and point E was located on the hole of the retention screw of implant 3.

All of the SGs were zeroed and calibrated before each loading, and a vertical load of 30 kg<sup>14</sup> was applied for 10 seconds, using a universal load-testing machine (DL-1000; Emic, São José dos Pinhais, Brazil). The magnitude of microstrain on each SG was recorded in units of microstrain ( $\mu\epsilon$ ). This procedure was repeated 2 more times, making a total of 3 readings per loading point (Figure 3).



**FIGURES 1–3.** **FIGURE 1.** Reproduction of wax patterns under polyurethane block. **FIGURE 2.** Strain gauge (SG) locations: SG 1 mesially to implant 1; SG 2 and SG 3 mesially and distally to implant 2; respectively, and SG 4 distally to implant 3. **FIGURE 3.** Detail of static vertical loading on loading point A.

### Statistical analysis

As an SG is only capable of detecting strain in a limited sector of the peri-implant area, it is more or less a matter of chance whether tensile or compressive forces are recorded. In short, negative values refer to compressive forces and positive values refer to tensile forces during stress and strain analyses. Therefore, negative values do not imply a value below zero.

To compare the magnitude of microstrain resulting from the type of implant/abutment joint, type of coping, and loading point, the positive and negative strains recorded in the SG analysis were transformed into absolute values,<sup>9,10,15,16</sup> which were used to calculate the mean values of microstrain of 4 SG.

The experimental variables under study were implant/abutment joint (external and internal), coping (plastic and prefabricated), and loading point (A, B, C, D, E). This experiment followed a factorial scheme of the  $2 \times 2 \times 5$  type. The variable response was the mean microstrain value obtained in the SG analysis. The experimental unit was the prosthetic superstructure. Twenty prosthetic superstructures were randomly assigned to 4 experimental conditions, implant/abutment joint (external and internal) and copings (plastic and machined).

The 100 values obtained were submitted to statistical analysis using the following statistical softwares: GraphPad-Prism (GraphPad Software, version 4.00, 2003, La Jolla, Calif), Minitab (Minitab, version 14.12, 2004, State College, Calif), and Statix (Analytical Software Inc, version 8.0, 2003, Tallahassee, Fla). The descriptive statistics consisted of means and standard deviations. The inferential statistics consisted of an analysis of variance of repeated measurements of 3 factors (implant/abutment joint, coping and loading point), in which the variable loading point was considered the repeated factor. The study of the interaction effect was conducted by utilizing

graphs and by a Tukey multiple-comparison test. Significance level was set at 5%.

### RESULTS

Table 1 presents the means and standard deviations of microstrain ( $\mu\epsilon$ ) obtained from the mean of 4 SGs for implant/abutment joint (EH and IH) and for coping (machined and plastic) at each loading point.

Results of the 3-factor repeated measures analysis of variance for the experimental conditions are presented in Table 2. There were statistically significant interaction effect between the implant/abutment joint types and loading point variables ( $P = .001$ ). There was a statistically significant effect for implant/abutment joint ( $P = .001$ ) and loading point ( $P = .001$ ). A Tukey multiple comparison test was then applied to compare the means values of microstrain for 2 levels of the implant-abutment factor and 5 levels of the loading point factor (Table 3).

### DISCUSSION

When an occlusal load is applied to an implant, the load is partially transferred to the bone, and the highest stresses occur in the implant's most cervical region. This phenomenon is due to one of the principles of engineering, that is, when 2 materials are in contact with each other and 1 of them is loaded, the stresses will be higher at the materials' initial point of contact.<sup>17</sup> Moreover, the cervical region of the implant is the site where the greatest microstrains occur,<sup>15,18</sup> independently of the type of bone, the design of the implant,<sup>19</sup> the configuration of the prosthesis, and the load.<sup>20</sup>

TABLE 1

Mean ( $\pm$  SD) values of microstrain ( $\mu\epsilon$ ) obtained from mean of 4 strain gauges at each loading point for the external and internal hexagon and for plastic and machined copings

Implant/Abutment Joint	Copings	Loading Point				
		A	B	C	D	E
External hexagon	Plastic, n = 5	130.7 $\pm$ 11.3	149.6 $\pm$ 23.2	206.0 $\pm$ 32.7	228.4 $\pm$ 52.9	221.7 $\pm$ 57.4
	Machined, n = 5	143.8 $\pm$ 47.3	177.9 $\pm$ 54.1	220.8 $\pm$ 86.0	286.5 $\pm$ 59.4	214.2 $\pm$ 43.9
Internal hexagon	Plastic, n = 5	296.6 $\pm$ 77.7	240.8 $\pm$ 42.4	310.3 $\pm$ 19.9	461.6 $\pm$ 59.5	440.2 $\pm$ 43.2
	Machined, n = 5	293.4 $\pm$ 64.0	238.2 $\pm$ 51.8	310.9 $\pm$ 56.1	423.9 $\pm$ 55.4	438.3 $\pm$ 42.8

TABLE 2  
Results of the 3-way repeated measures analysis of variance

Effect	DF	SS	MS	F	P Value
Implant-abutment joint	1	543 744	543 744	71.62	.0001*
Coping	1	959	959	0.13	.7269
Implant-abutment joint/coping	1	5749	5749	0.76	.3971
Residue I	16	121 477	7592		
Loading point	4	349 624	87 406	58.40	.0001*
Implant-abutment joint/loading point	4	73 295	18 324	12.24	.0001*
Coping/loading point	4	912	228	0.15	.9613
Implant-abutment joint/coping/loading point	4	7553	1888	1.26	.2943
Residue II	64	95 785	1497		
Total	99	1 199 098			

\*P < .05.

In this present study, SGs were strategically bonded on the polyurethane block, tangentially to the implant platform to observe the region with the highest concentration of stresses during the application of loads. This laboratory simulation model was selected to obtain baseline information about the distribution pattern of strain. This positioning of the SGs has also been used in previous studies.<sup>9,10,21,22</sup> The flat surface of the polyurethane block made the positioning and bonding of the SGs simpler and more precise than in other studies, which opted for bonding on the implants,<sup>23,24</sup> the abutments,<sup>16,24</sup> and the metal structures of the prosthesis.<sup>9,15</sup>

In this SG analysis, the implant-abutment joint effect and the implant-abutment joint/loading point interaction demonstrated statistically significant differences. From a biomechanical perspective, the fixture-abutment joint designs should have junctions that reduce the peak bone interface stresses and strains<sup>25</sup>. In the EH design, the abutment screw is the only element that keeps the fixture and the abutment assembled. Otherwise, in the IH design, friction plays a crucial role in maintaining the screw-joint in addition to the torque applied during abutment tightening. These fundamental differences in design affect the mechanical behaviors of implants.<sup>2,25</sup> Maeda et al<sup>24</sup> verified differences in the force distribution patterns between implants with EH and those with IH connection systems using SG analysis and observed that there was no statistically significant difference between the 2 types of abutment connections systems under vertical load. However,

these authors simulated a single-implant prosthesis and the vertical load was applied on the abutment. In recent study, Nishioka et al<sup>26</sup> found no statistically significant differences between microstrain values obtained with an EH design and an IH design during the fixation of implant-supported fixed partial prostheses. In contrast, the result of the present study suggests that axial loading on the superstructures and the type of implant-abutment joint could change the strain distribution patterns around implants, decreasing or increasing the magnitude of microdeformation.

In this present study, the coping effect and the coping/loading point interaction showed no statistically significant difference. This finding suggests that the type of coping, plastic or machined, does not affect the magnitude of microstrain when an implant-supported fixed prosthesis is axially loaded, and that the behavior of both copings followed the same pattern at all of the loading points. Previous SG studies have reported similar results,<sup>9-11</sup> with fixed partial prostheses screwed onto implants, made from plastic or machined copings, producing the same magnitude of microstrain during tightening of the retention screws, without any statistically significant difference between plastic and machined copings before<sup>9,10</sup> and after<sup>11</sup> the application of a dental ceramic. Furthermore, studies to evaluate the fit of the abutment/prosthesis interface have demonstrated that the precision of unitary metallic structures obtained with machined copings is better than that obtained with plastic copings.<sup>27,28</sup> However, it

TABLE 3  
Tukey test ( $\alpha = 0.05$ ) of the mean microstrain ( $\mu\epsilon$ ) for interaction between the implant/abutment joint and loading point variables

Loading Point	Implant- Abutment Joint†	Mean	Homogeneous Groups*			
A	EH	137.24				F
	IH	295.00	B	C		
B	EH	163.73				F
	IH	239.49		C	D	E
C	EH	213.41			D	E
	IH	310.63	B			
D	EH	257.42	B	C	D	
	IH	442.77	A			
E	EH	217.98		C	D	E
	IH	439.28	A			

\*Same letters denotes no significant difference.  
†EH indicates external hexagon; IH, internal hexagon.

should be noted that the care involved in handling multiple prostheses is very different from that involved in handling single ones, and the complexity of the laboratory procedures increases proportionally to the number of fixations involved.

With regards to the loading point effect, a statistically significant difference was found, suggesting that symmetrical loading points, A versus E and B versus D, did not produce similar magnitudes of microstrain. The superstructures showed satisfactory fit, which was confirmed by direct vision in conjunction with tactile sensation through an explorer. However, these methods are not able to detect slight distortions of the prosthesis on the implant,<sup>13</sup> probably caused by casting procedures of the implant-supported fixed partial prosthesis. This finding suggests that the fit of the cast metal rods was not homogeneous, that is, the fit attained by the cast metal rods in implant 3 may have differed from that found in implant 1, which in turn may also have differed from the fit obtained in implant 2. Thus, the nonhomogeneous fit may have influenced the distribution of strains, producing different magnitudes of microstrain, even when the load was applied on equidistant and symmetrical points.

In the present study, it was also observed that when loads were applied on loading points A, B, D, and E, which were positioned on and close to the implants at the extremities, the largest microstrains occurred in the closest SGs, indicating that the amount of load transmitted to the implant and the strains generated in the bone depend on the location where the load is applied on the prosthesis. In contrast, when loads were applied on loading point C, which was positioned on the central implant, the greatest microstrains occurred in the most distant SGs, indicating that the implants at the extremities were more loaded. These results suggest that the strains generated by occlusal contacts located close to the central implant of the screwed fixed partial prosthesis supported on 3 implants are distributed to the implants at the extremities, while the strains generated by occlusal contacts positioned close to the implants at the extremities concentrate in those implants. A possible explanation for that might be because of the presence of a bilateral connection of middle implant (point C) compared with a unilateral connection of peripheral implant. A bilateral connection would possibly dissipate the applied strain through the framework more than unilateral connections.<sup>29</sup>

According to Frost<sup>4</sup> and Wiskott and Belser,<sup>5</sup> bone homeostasis occurs when the level of microstrain remains within the range of 100 to 2000  $\mu\epsilon$  and 50 to 1500  $\mu\epsilon$ , respectively. In Table 1, most of the microstrain values obtained for implant-abutment joint and copings remained within the level of bone homeostasis, or normal load. This finding suggests that when a partial fixed prosthesis of 3 elements and supported by 3 implants is loaded axially, with occlusal contacts positioned between the implants and as close as possible to the latter, bone resorption around the implants and occlusal overload can be minimized.

Limitations in the model of this study must be taken into account when interpreting the results. This is an *in vitro* study based on a homogenous model with known mechanical properties instead of bone. This not only allowed for proper strain measurements but also 100% implant-model material contact. *In vivo*, additional variables, such as bone density,

implant stability, and bone-to-implant contact, would have to be considered. The interimplant relationships represented a straight-line configuration of the implants, which seems also to be a simplified situation compared with a curved distribution with a longer segment splinted. The flat occlusal surface of the superstructures did not represent the real clinical situation; variables such as cusp inclination, occlusal table and location, and direction and magnitude of applied occlusal forces on the superstructures could change the results of this study.

## CONCLUSION

Based on the current results, the type of implant-abutment joint presented different mechanical behavior under axial loads, and the IH connection displayed higher values of microstrain than the EH. The type of coping did not interfere in the magnitude of microstrain under axial loading, and the location of the applied axial loads affected the magnitude of microstrain.

## ABBREVIATIONS

EH: external hexagon

IH: internal hexagon

SG: strain gauge

## REFERENCES

1. Isidor F. Histological evaluation of peri-implant bone at implants subjected to occlusal overload or plaque accumulation. *Clin Oral Implants Res.* 1997;8:1–9.
2. Isidor F. Loss of osseointegration caused by occlusal load of oral implants. A clinical and radiographic study in monkeys. *Clin Oral Implants Res.* 1996;7:143–152.
3. Sahin S, Çehrelci MC, Yalçın E. The influence of functional forces on the biomechanics of implant-supported prostheses—a review. *J Dent.* 2002;30:271–282.
4. Frost MH. Wolff's law and bone's structural adaptations to mechanical usage: an overview for clinicians. *Angle Orthod.* 1994;64:175–188.
5. Wiskott HWA, Belser UC. Lack of integration of smooth titanium surfaces: a working hypothesis based on strains generated in the surrounding bone. *Clin Oral Implants Res.* 1999;10:429–444.
6. Rangert BR, Sullivan RM, Jemt TM. Load factor control for implants in the posterior partially edentulous segment. *Int J Oral Maxillofac Implants.* 1997;12:360–370.
7. Pjetursson BE, Tan K, Lang NP, Bragger U, Egger M, Zwahlen M. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. I. Implant-supported FPDs. *Clin Oral Implants Res.* 2004;15:625–642.
8. Moberg LE, Kondell PA, Sagulin GB, et al. Branemark system and ITI dental implants system for treatment of mandibular edentulism. A comparative randomized study: 3-year follow-up. *Clin Oral Implants Res.* 2001;12:450–461.
9. 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.
10. Heckmann SM, Karl M, Wichmann MG, Winter W, Graef F, Taylor TD. Loading of bone surrounding implants through three-unit fixed partial denture fixation: a finite-element analysis based on *in vitro* and *in vivo* strain measurements. *Clin Oral Implants Res.* 2006;17:345–350.
11. Karl M, Rösch S, Graef F, Taylor TD, Heckmann SM. Strain situation after fixation of three-unit ceramic veneered implant superstructures. *Implant Dent.* 2005;14:157–165.
12. Karl M, Taylor TD, Wichmann MG, Heckmann SM. *In vivo* stress

- behavior in cemented and screw-retained five-unit implant FPDs. *J Prosthodont.* 2006;15:20–24.
13. Kan JY, Rungcharassaeng K, Bohsali K, Goodacre CJ, Lang BR. Clinical methods for evaluating implant framework fit. *J Prosthet Dent.* 1999; 81:7–13.
  14. Mericske-Stern R, Assal P, Merickse E, Bürgin W. Occlusal force and oral tactile sensibility measured in partially edentulous patients with ITI implants. *Int J Oral Maxillofac Implants.* 1995;10:345–353.
  15. Karl M, Wichmann MG, Winter W, Graef F, Taylor TD, Heckmann SM. Influence of fixation mode and superstructure span upon strain development of implant fixed partial dentures. *J Prosthodont.* 2008;17:3–8.
  16. Seong WJ, Koriotoh TWP, Hodges JS. Experimentally induced abutment strains in three types of single-molar implant restorations. *J Prosthet Dent.* 2000;84:318–326.
  17. Isidor F. Influence of forces on peri-implant bone. *Clin Oral Implants Res.* 2006;17(special issue 2):8–18.
  18. Kim Y, Oh TJ, Misch CE, Wang HL. Occlusal considerations in implant therapy: clinical guidelines with biomechanical rationale. *Clin Oral Implants Res.* 2005;16:26–35.
  19. Tada S, Stegaroiu R, Kitamura E, Miyakawa O, Kusakari H. Influence of implant design and bone quality on stress/strain distribution in bone around implants: a 3-dimensional finite element analysis. *Int J Oral Maxillofac Implants.* 2003;18:357–368.
  20. Stegaroiu R, Sato T, Kusakari H, Miyakawa O. Influence of restoration type on stress distribution in bone around implants: a three-dimensional finite element analysis. *Int J Oral Maxillofac Implants.* 1998;13: 82–90.
  21. Çehreli MC, Akça K. Narrow-diameter implants as terminal support for occlusal three-unit FPDs: a biomechanical analysis. *Int J Periodontics Restorative Dent.* 2004;24:513–519.
  22. Nishioka RS, Vasconcellos LGO, Melo Nishioka LN. External hexagon and internal hexagon in straight and offset implant placement: strain gauge analysis. *Implant Dent.* 2009;18:512–520.
  23. Akça K, Çehreli MC, Iplikçioğlu H. A comparison of three-dimensional finite element stress analysis with *in vitro* strain gauge measurements on dental implants. *Int J Prosthodont.* 2002;15:115–121.
  24. Maeda Y, Satoh T, Sogo M. *In vitro* differences of stress concentrations for internal and external hex implant-abutment connections: a short communication. *J Oral Rehabil.* 2006;33:75–78.
  25. Çehreli M, Sahin S, Akça K. Role of mechanical environment and implant design on bone tissue differentiation: current knowledge and future contexts. *J Dent.* 2004;32:123–132.
  26. Nishioka RS, Nishioka LN, Abreu CW, de Vasconcellos LG, Balducci I. Machined and plastic copings in three-element prostheses with different types of implant-abutment joints: a strain gauge comparative analysis. *J Appl Oral Sci.* 2010;18:225–230.
  27. Carr AB, Brunski JB, Hurley E. Effects of fabrication, finishing, and polishing procedures on preload in prostheses using conventional “gold” and plastic cylinders. *Int J Oral Maxillofac Implants.* 1996;11:589–598.
  28. Kano SC, Bonfate G, Hussne R, Siqueira AF. Use of base metal casting alloys for implant framework: marginal accuracy analysis. *J Appl Oral Sci.* 2004;12:337–343.
  29. Abu-Hammad O, Khraisat A, Dar-Odeh N, Jagger DC, Hammerle CH. The staggered installation of dental implants and its effect on bone stresses. *Clin Implant Dent Relat Res.* 2007;9:121–127.