The effect of implant diameter on strain around implants retaining a mandibular overdenture with Locator attachments: An in vitro study

Moustafa Abdou ELSYAD¹, Ahmed Abdelsalam ELHDDAD² and Ahmed Samir KHIRALLAH¹

¹ Department of Removable Prosthodontics, Faculty of Dentistry, Mansoura University, Egypt
² Department of Removable Prosthodontics, Faculty of Dentistry, Tripoli University, Libya
Corresponding author, Moustafa Abdou ELSYAD; E-mail: M_syad@mans.edu.eg

This study evaluated the effect of implant diameter on strain around implants retaining mandibular overdentures with Locator attachments. Three mandibular acrylic resin models were constructed with 2 implants inserted in canine areas and classified according to implant diameter into 3 groups: large (4.2 mm), medium (3.7 mm), and small (3.3 mm) diameter implants. Duplicate dentures were connected to the implants with Locator attachments. Four strain gauges were bonded to the acrylic resin at mesial, distal, buccal and lingual surfaces of each implant and strain was measured at loading and non-loading sides during 1st premolar and 1st molar loading. Small and large diameter implants recorded the highest and the lowest strain, respectively. Buccal and lingual sites recorded the highest strain, and mesial site recorded the lowest. First premolar loading recorded significant higher strain than first molar loading. The largest possible implant diameter is recommended to minimize strains around implants retaining mandibular overdentures with Locator attachments.

Keywords: Diameter, Strain, Implant overdentures, Locator

INTRODUCTION

The 2-implant overdenture is an attractive treatment because of its relative simplicity, minimal invasiveness, and economy1). The configuration of an implant has long been considered an essential requirement for implant success2). Previous research showed that stresses in the bone surrounds the implants were influenced by the implant dimensions3-9). Animal experiments 10) and clinical studies 11-13) have shown that inappropriate loading causes excessive stress in the bone around the implant and may result in bone resorption and implant failure.

Implant diameter affected stress more in cortical bone at the crest of the alveolar ridge2) and had a more significant effect than implant length to relieve crestal stress and strain concentrations14). The implant diameter influence the interfacial stress, and the effects of changing implant diameter is significantly noticed in the cortical bone15). Narrow-diameter implants (<3.7 mm) are indicated in cases of alveolar bone loss prior to tooth extraction as a result of periodontal disease or when the buccolingual width of the edentulous ridge is insufficient to place conventional implants16,17).

Locator attachments have recently come into widespread use and are now available from several implant manufacturers. These attachments are self-aligning, and have dual (inner and outer) retention mechanism18). Locators can be used in patients who have limited inter-arch distance to reduce denture base deformation and fracture thanks to their low profile19). Moreover, Locators can compensate for angle corrections of up to 40°20). The mode of retention of the Locator attachments is frictional contact, which arises from a dimensional misfit between the slightly oversized nylon male insert and the smaller diameter of the inner ring of the female abutment21).

Reviewing the literature, the effect of implant diameter on peri-implant crestal strain was investigated in several finite element studies (FEA)2,9,14,15,22-28). However, FEA has several drawbacks. Structures in FEA model are assumed to be homogeneous isotropic and linearly elastic. The properties of the living tissues, however, are different. In addition, most FEA models assumed a state of optimal osseointegration for the interface between the bone and implant, which does not occur exactly in clinical situations14). Therefore, it is advisable to focus on qualitative rather than quantitative data from these analyses23,29). On the other hand, electrical strain gauges have been used extensively for quantitative analysis of the stresses around implants supporting mandibular overdentures30).

The effect of implant diameter on strain around implants retaining mandibular overdentures with Locator attachments was not investigated. Accordingly, the aim of this study was to evaluate, by means of strain gauge analysis, the effect of different implant diameters on strain around two-implants retaining a mandibular over denture with locator attachments. The authors hypothesized that changing implant diameter would not affect peri-implant strain.

MATERIALS AND METHODS

Experimental mandibular models
An edentulous mandibular model was duplicated into 3
experimental heat cure acrylic resin models (clear heat curing acrylic resin, Acroston, Egypt). The model had 4.6 mm ridge width at the canine areas (measured using a pointed caliper) to allow placement of implants with different diameters. The edentulous ridge was covered with 1.5 mm silicone layer (Softliner®, Promedica, Neumünster, Germany) to simulate oral mucosa\textsuperscript{31,32}. For each model, two laboratory implants (13 mm length, TioLogic, Dentaurum, Germany) were placed bilaterally in the canine regions parallel to each other and perpendicular to the residual ridge using a parallometer milling machine (Bego Bremer Goldschagerei Wihl. Herbst, Bremen, Germany). The implants were fixed to the models using a resin cement (Superbond CB, Sun Medical, Kyoto, Japan) to simulate osseointegration\textsuperscript{31}.

According to the implant diameter, the experimental models were divided into 3 groups: group I: included implants with large diameter (4.2 mm), group II: included implants with medium diameter (3.7 mm), and group III: included implants with small diameter (3.3 mm) (Fig. 1). The Locator abutments (gingival height 3 mm, TioLogic) for each model were screwed to the laboratory implants using 35 Ncm torque.

**Experimental overdentures**

For each acrylic model, a rubber base impression (Zetaplus, Zhermack, Italy) was made and poured to obtain a stone model. Wax-up trial denture base was constructed over one of the stone models and artificial teeth were arranged on the trial denture base. The height of the occlusal plane was adjusted to the level between the upper and middle third of retromolar pad. A rubber base impression of the wax-up trial denture base was made to produce a mold for fabrication of 3 duplicate dentures. The upper piece of the mold was negative of the denture polished surface and the teeth. Artificial teeth were then inserted into the mold. Fifteen identical dentures (5 dentures/group) were obtained by pouring molten base plate wax into the intervening space between the silicone mold and the stone casts. The sample size (5 dentures/group) was calculated based on the results of a previous study\textsuperscript{30} in which the author compared peri-implant strains of implant retained mandibular overdentures between groups using a similar methodology. The waxed dentures were then flanked using heat cured acrylic resin (clear heat curing acrylic resin, Acroston) to obtain 15 duplicate dentures.

The Locator black processing inserts were attached to Locator matrix and the assembly was inserted plugged into Locator abutments on the acrylic models. The Locator matrices were picked up to each corresponding denture using an autopolymerized acrylic resin. The black processing inserts were removed and pink nylon inserts (light retention, 1.365 g) were fitted to the locator matrix with a locator press tool (Fig. 2).

**Strain gauge analysis**

1. Strain gauge fixation

For each model (group), 4 linear strain gauges (KFG-1-120-C1-1L1M2R; KYOWA electronic instruments, Tokyo, Japan; resistance 119.6±0.4% Ω; gauge length: 1 mm; gauge factor: 2.08±1.0%) were bonded to the acrylic resin at mesial, distal, buccal and lingual surfaces of each implant\textsuperscript{33} using a cyanoacrylate adhesive (CC-33A, EP-34B, KYOWA electronic instruments) to monitor the strain around the implants during load application (Fig. 3). All gauges were positioned on the crest of the ridge perpendicular to the implant long axis. At least 5 mm of the silicone mucosal simulation around mesial, distal, buccal and lingual surfaces of each implant was removed by using sharp scalpel to provide space for cementation of the gauges. The acrylic resin around each implant was prepared to be flat and smoothened with fine sandpaper for strain gauge bonding to avoid incremental apparent

---

![Fig. 1](image1.png)  **Fig. 1** Laboratory implants in position in the acrylic models.
A: Small diameter implants, B: Medium diameter implants, and C: Large diameter implants.

![Fig. 2](image2.png)  **Fig. 2** Locator pink inserts on the fitting surface of the overdentures.
strain. The fine lead wires of the gauges were fixed to the acrylic resin model to avoid accidental displacement of the wire that may affect the accuracy of the readings. The wire terminals of the 8 strain gauges were connected to a quarter bridge circuit of a multichannel strain meter (Model 8692, Tinsely precision instruments, Surrey, UK). The microvoltage output was converted into microstrain by a software (Kyowa PCD 300A).

2. Strain gauge calibration
Before strain measurements, a calibration experiment to the gauges was made to assess the repeatability of force measurements and the linearity of the gauges. A cyclic load ranging from 10 to 60 N was applied 5 times in 10 N steps on the occlusal surface of mandibular denture using a loading device (LLOYD LRX, LLOYD instruments, Fareham, Hampshire, UK) to age the gauges. The purpose of “aging” was to minimize hysteresis, a lagging or retardation of the effect when forces acting upon the denture are changed.

3. Strain gauge measurements
A fully digitized universal testing machine (LLOYD LRX, LLOYD instruments) was used to apply a vertical static load of 100 N for 15 s. This amount of load simulates a moderate level of biting force on an implant-retained overdenture. The load was applied in compression mode at a cross head speed of 0.5 mm/min unilaterally over first premolar and first molar positions. The point of load application was selected at the site of central occlusal fossa of the 1st premolar and 1st molar (Fig. 4) on the loading side. The point of load application was notched with a diamond bur to accommodate the tip of the loading pin for reproducibility and to prevent slippage of the pin. Strains were measured at mesial, distal, buccal and lingual peri-implant surfaces at loading (left) and non-loading (right) sides.

All measurements were repeated 5 times for each experimental overdenture, allowing at least 5 min for heat dissipation. The mean recorded microstrain from the 5 measurements was subjected to statistical analysis.

**Statistical analysis**
General linear model (two-Way ANOVA) was used to compare recorded microstrain values between different groups (large diameter, medium diameter and small diameter implants) and between different surfaces of measurements (mesial, distal, buccal and lingual) followed by post hoc test for multiple comparison using Bonferroni correction. To compare recorded microstrains between loading positions (premolar and molar positions) and loading sides (loading and non-loading sides), paired samples t-test was used. p Value is significant if it was less than 0.05 at confidence interval 95%. The SPSS statistical package for social science version 22 (SPSS, Chicago, IL, USA) was used for data analysis.

**RESULTS**
Comparisons of overall microstrain values between groups, strain gauge positions, loading positions and loading sides are presented in Tables 1 to 4 respectively. Small diameter implants recorded the highest strain, followed by medium diameter implants, and large diameter implants recorded the lowest strain (Table 1). Buccal and lingual sites recorded the highest strain (without significant differences), followed by distal site and mesial site recorded the lowest strain (Table 2). First premolar loading recorded significantly higher strain than first molar loading (Table 3). Non-loading side recorded significantly higher strain than loading sides (Table 4).

Comparisons of microstrain values between groups and between strain gauge position at loading and non-loading sides are presented in Tables 5 and 6 respectively.

For all strain gauges, loading positions and loading sides, small diameter implants recorded the highest strain, followed by medium diameter implants and the lowest strain was recorded with large diameter implants.
Table 1  Comparison of total microstrains between groups

|                      | Mean  | St. error | F value | ANOVA p | Post hoc test (Bonferroni) |
|----------------------|-------|-----------|---------|---------|---------------------------|
| Large diameter       | −7.125| 1.525     |         |         | A                         |
| Medium diameter      | −29.937| 1.525   | 9311.202| 0.00*   | B                         |
| Small diameter       | −241.438| 1.525  |         |         | C                         |

*p is significant at 0.05 level of significance. Different upper case letter indicates significant differences between groups.

Table 2  Comparison of total microstrains between strain gauge surfaces

|          | Mean   | St. error | F value | ANOVA p | Post hoc test (Bonferroni) |
|----------|--------|-----------|---------|---------|---------------------------|
| Distal   | −45.917| 1.761     |         |         | A                         |
| Lingual  | −114.250| 1.761    | 443.505 | 0.00*   | B                         |
| Buccal   | −114.583| 1.761    |         |         | B                         |
| Mesial   | −16.750| 1.761     |         |         | C                         |

*p is significant at 0.05 level of significance. Different upper case letter indicates significant differences between groups.

Table 3  Comparison of total microstrains between first premolar and first molar loading positions

|                  | Mean   | St. error | Paired samples t-test |
|------------------|--------|-----------|-----------------------|
| First premolar   | −82.458| 1.245     | 0.00*                 |
| First molar      | −63.292| 1.245     |                       |

*p is significant at 5% level.

Table 4  Comparison of total microstrains between loading and non-loading sides

|                  | Mean   | St. error | Paired samples t-test |
|------------------|--------|-----------|-----------------------|
| loading (right)  | −54.333| 1.245     | 0.00*                 |
| non-loading (left)| −91.417| 1.245     |                       |

*p is significant at 5% level.

(ANOVA, p=0.00).

At loading side during first premolar loading, lingual surfaces recorded the highest strain, followed by buccal surfaces, distal surfaces and the lowest strain was recorded with mesial surface. During first molar loading, distal surface recorded the highest strain, followed by mesial surfaces, and the lowest strain was recorded with buccal and lingual surfaces (Table 5).

At non-loading side during first premolar loading, mesial surfaces recorded the highest strain, followed by buccal surfaces, lingual surfaces and the lowest strain was recorded with distal surface. During first molar loading, lingual surface recorded the highest strain, followed by mesial surfaces, buccal, and the smallest

strain was recorded with distal surface (Table 6).

With exception of buccal and mesial gauges (for large and small diameter implants) and mesial gauges (for medium diameter implants) during 1st premolar loading, loading side recorded significant higher strain than non-loading side (paired samples t-test, p<0.03). With exception of distal, buccal and mesial gauges (for large diameter implants) and distal gauges (for medium diameter implants) during 1st molar loading, non-loading side recorded significant higher strain than loading side (paired samples t-test, p<0.039).
Table 5  Comparison of microstrains between groups and between strain gauge surfaces on loading side

|                         | Large diameter | Medium diameter | Small diameter | 2 way ANOVA (p) |
|-------------------------|----------------|----------------|----------------|-----------------|
| First premolar loading  |                |                |                |                 |
| Distal (X±SD)           | 10.0±.00 a,A   | 116.0±9.62 b,A | −209.0±67.2 c,A| 0.00*           |
| Lingual (X±SD)          | −53.0±2.74 a,B | −151.0±4.18 b,B| −521.0±5.48 c,B| 0.00*           |
| Buccal (X±SD)           | −13.0±2.74 a,C | −94.0±9.62 b,C | −239.0±2.24 c,C| 0.00*           |
| Mesial (X±SD)           | −1.0±2.24 a,D  | 68.0±2.74 b,D  | −55.0±7.91 c,D | 0.00*           |
| 2 way ANOVA (p)         | 0.00*          | 0.00*          | 0.00*          | —               |
| First molar loading     |                |                |                |                 |
| Distal (X±SD)           | 48.0±5.70 a,A  | 54.0±12.94 b,A | −172.0±6.71 c,A| 0.00*           |
| Lingual (X±SD)          | 16.0±2.24 a,C  | −13.0±2.74 b,B | −64.0±4.18 c,B | 0.00*           |
| Buccal (X±SD)           | 9.0±2.24 a,B   | −10.0±0.00 b,B | −58.0±2.74 c,B | 0.00*           |
| Mesial (X±SD)           | −40.0±6.52 a,C | 34.0±2.24 b,C  | 73.0±1.58 b,D  | 0.00*           |
| 2 way ANOVA (p)         | 0.00*          | 0.00*          | 0.00*          | —               |

X: mean, SD: standard deviation. *p is significant at 5% level. The different lower case letter in the same raw indicate a significant difference between groups. The different upper case letter in the same column indicate a significant difference between surfaces (Bonferroni test, p<0.05).

Table 6  Comparison of microstrains between groups and between strain gauge surfaces on non-loading side

|                         | Large diameter | Medium diameter | Small diameter | 2 way ANOVA (p) |
|-------------------------|----------------|----------------|----------------|-----------------|
| First premolar loading  |                |                |                |                 |
| Distal (X±SD)           | −9.0±2.24 a,A  | −49.0±4.18 b,A | −70.0±0.00 c,A | 0.00*           |
| Lingual (X±SD)          | 22.0±2.74 a,C  | 59.0±2.24 b,B  | −256.0±9.62 c,B| 0.00*           |
| Buccal (X±SD)           | 26.0±2.24 a,C  | 79.0±4.18 b,C  | −319.0±27.70 c,C| 0.00*           |
| Mesial (X±SD)           | −87.0±4.47 a,B | 135.0±3.54 b,D | −368.0±13.51 c,D| 0.00*           |
| 2 way ANOVA (p)         | 0.00*          | 0.00*          | 0.00*          | —               |
| First molar loading     |                |                |                |                 |
| Distal (X±SD)           | −3.0±2.74 a,A  | 5.0±0.00 b,A   | −242.0±13.04 c,A| 0.00*           |
| Lingual (X±SD)          | −35.0±6.12 a,B | 127.0±4.47 b,D | −816.0±43.50 c,C| 0.00*           |
| Buccal (X±SD)           | −9.0±2.24 a,C  | 39.0±4.18 b,C  | −171.0±8.94 c,D | 0.00*           |
| Mesial (X±SD)           | 14.0±2.24 a,C  | 80.0±3.54 b,B  | −346.0±19.17 c,B| 0.00*           |
| 2 way ANOVA (p)         | 0.00*          | 0.00*          | 0.00*          | —               |

X: mean, SD: standard deviation. *p is significant at 5% level. The different lower case letter in the same raw indicate a significant difference between groups. The different upper case letter in the same column indicate a significant difference between surfaces (Bonferroni test, p<0.05).

DISCUSSION

Strain gauges were bonded to the crest of the ridge around the implants because peri-implant stresses and bone loss usually initiated at the alveolar crest around the implant’s neck and possible overloading could occur from compression of cortical bone at alveolar crest. The load was applied unilaterally to reproduce mastication on the preferred chewing side of the patient. The first molar was chosen for loading because maximum occlusal...
forces are often exerted in this region where there is maximum contraction of the elevator muscles\(^{37}\). To evaluate the effect of load application over the implant position and the effect of different loading positions on peri-implant strain, loading on first premolar position was performed. Premolar loading was also used in other \textit{in vitro} studies\(^{22,25,26}\) studies in which the authors reported that increasing implant diameter would result in reduction in crestal bone strains. In these studies, implants were placed in mandibular bone in anterior\(^{14,15}\), premolar\(^{26}\), and molar\(^{22,26}\) positions. Some of these studies found that the influence of implant diameter on crest bone strains dominates over the effect of the implant’s length\(^{2,9,14,15,22-26}\) especially in cortical bone. Petrie and Williams\(^{24}\) compared interactive effects of implant diameter, length, and taper on crestal bone strains around implants inserted in premolar section of the mandible. They found that increasing implant diameter resulted in as much as a 3.5-fold reduction in strain on the alveolar crest. They added that narrow, short implants should be avoided, especially in low-density bone. Ding \textit{et al.}\(^{14}\) evaluated the effect of the diameter (ranged from 3.3 to 4.8 mm) and length on the strain distribution of the crestal bone around implants inserted in the anterior region of the mandible. They found that large implant diameter decreased strain on the alveolar crest, especially under buccolingual loading as compared with vertical loading. In line with these observations, several clinical studies reported higher survival rates and reduced crestal bone loss (means ranged between 0.19 and 0.57 mm) for wide-diameter implants\(^{40,41}\).

The increased strain at lingual and buccal surfaces of the implants during posterior loading agreed with the findings of Ichikawa \textit{et al.}\(^{45}\) who reported that occlusal stress had a tendency to concentrate on the implant, especially in the areas distal to the implant. Similarly, Celik and Uludag\(^{46}\) found in a photoelastic stress analysis that the distal side of implants supporting overdenture showed higher peri-implant stress than the mesial surface.

First premolar loading showed significant higher strain than first molar loading. This was somewhat unexpected, since the increased lever arm when the point of load application moved posteriorly was expected to increase peri-implant strain. The increased peri-implant strain during first premolar loading may be due to the load application was nearly above the implant position, while during molar loading, the cushioning effect of the mucosal simulation together with the hinge resiliency of locator inserts may dilute the effect of load on implants and decrease the peri-implant strains. The increased strain during first premolar loading compared...
to first molar loading is in line with the observation of Porter et al. who stated that the forces on an implant became greater when the load was applied directly to the prosthesis over or near the implant. Federich and Caputo evaluated the effect of different load positions (over the implant, at the second premolar, and at the second molar) on peri-implant strain. The authors found that more posteriorly applied loads resulted in reducing the load to the implant in anterior region. Therefore, it is important to direct the forces of occlusion to the molar areas and pick-up of the Locator attachments to the denture base intrarorally to relieve stress around the implants when Locator attachments are used.

For majority of strain gauges (except buccal and mesial gauges for large and small diameter implants and mesial gauges for medium diameter implants), loading side recorded significant higher strain than non-loading side during first premolar loading. A similar observation was also noted in other strain gauge and finite element studies. For majority of strain gauges (except distal, buccal and mesial gauges for large diameter implants and distal gauges for medium diameter implants) non-loading side recorded significant higher strain than loading side during first molar loading. This may be attributed to implants at loading side which may act as a fulcrum. Therefore, the denture tends to rotate and Locator attachment at non-loading side try to disengage. The double frictional flanges of the nylon inserts prevent the total disengagement and cause increased peri-implant strain at non-loading side. Therefore, it may be advantageous to balancing of the occlusion to distribute pressure on working and balancing side to avoid concentration of peri-implant strain one side.

Over all, the null hypothesis was rejected. The major shortcoming of this is the necessity to drive certain assumptions or to use materials that frequently do not simulate the complex nature of living tissues. Also, the simulated loads were applied vertically, although it is known that mastication forces occur in many directions. Therefore, further studies would be beneficial in evaluating the stress transfer under axial and offset load application.

CONCLUSIONS

Within the limitation of this in vitro strain gauge analysis, the following conclusions could be drawn:

1. The largest possible implant diameter, concentration of occlusal load on first molar area, balancing the occlusion to distribute pressure on working and balancing side and direct pick-up of the Locator attachments to the denture base intraorally are recommended to minimize peri-implant strains that may be associated with increased crestal bone loss when 2 implants are place at bilateral canine regions to retain 2-implant overdenture.

2. Clinical trials are needed to evaluate the effect of different implant diameters, loading conditions and type of occlusion on peri-implant crestal alveolar bone loss.

CONFLICT OF INTEREST

Authors have no conflict of interest with this article.

REFERENCES

1) Klemetti E, Lassila L, Lassila V. Biometric design of complete dentures related to residual ridge resorption. J Prosthodont Dent 1996; 75: 281-284.
2) Kong L, Gu Z, Li T, Wu J, Hu K, Liu Y, Zhou H, Liu B. Biomechanical optimization of implant diameter and length for immediate loading: a nonlinear finite element analysis. Int J Prosthodont 2009; 22: 607-615.
3) Pierrinsard L, Renouard F, Renault P, Barquins M. Influence of implant length and bicortical anchorage on implant stress distribution. Clin Implant Dent Relat Res 2003; 5: 254-262.
4) Himmlova L, Dostalova T, Kacovsky A, Konvickova S. Influence of implant length and diameter on stress distribution: a finite element analysis. J Prosthodont 2004; 91: 20-25.
5) Yokoyama S, Wakabayashi N, Shiota M, Ohyama T. The influence of implant location and length on stress distribution for three-unit implant-supported posterior cantilever fixed partial dentures. J Prosthodont 2004; 91: 234-240.
6) Ivanoff CJ, Grondahl K, Semnerby L, Bergstrom C, Lekholm U. Influence of variations in implant diameters: a 3- to 5-year retrospective clinical report. Int J Oral Maxillofac Implants 1999; 14: 173-180.
7) Misch CE. Implant design considerations for the posterior regions of the mouth. Implant Dent 1999; 8: 376-386.
8) Tawil G, Aboujaoude N, Younan R. Influence of prosthetic parameters on the survival and complication rates of short implants. Int J Oral Maxillofac Implants 2006; 21: 275-282.
9) Holmgren EP, Seckinger RJ, Kilgren LM, Mante F. Evaluating parameters of osseointegrated dental implants using finite element analysis —a two-dimensional comparative study examining the effects of implant diameter, implant shape, and load direction. J Oral Implantol 1998; 24: 80-88.
10) 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.
11) van Steenberghe D, Lekholm U, Bolender C, Folmer T, Henry H, Herrmann I, Higuchi K, Laney W, Linden U, Astrand P. Applicability of osseointegrated oral implants in the rehabilitation of partial edentulism: a prospective multicenter study on 558 fixtures. Int J Oral Maxillofac Implants 1990, 5: 272-281.
12) Edell R, Lekholm U, Rockler B, Branemark PI. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. Int J Oral Surg 1981; 10: 387-416.
13) Block MS, Gardiner D, Kent JN, Misiek DJ, Finger IM, Guerra L. Hydroxyapatite-coated cylindrical implants in the posterior mandible: 10-year observations. Int J Oral Maxillofac Implants 1996; 11: 626-633.
14) Ding X, Liao SH, Zhu XH, Zhang XH, Zhang L. Effect of diameter and length on stress distribution of the alveolar crest around immediate loading implants. Clin Implant Dent Relat Res 2009; 11: 279-287.
15) Faegh S, Muftu S. Load transfer along the bone-dental implant interface. J Biomech 2010; 43: 1761-1770.
16) Arisan V, Bolukbas N, Ersanli S, Ozdemir T. Evaluation of 316 narrow diameter implants followed for 5-10 years: a clinical and radiographic retrospective study. Clin Oral Implants Res 2010; 21: 296-307.
17) Elsyad MA. Patient satisfaction and prosthetic aspects with
mini-implants retained mandibular overdentures. A 5-year prospective study. Clin Oral Implants Res 2016; 27: 926-933.

18) Evtimovska E, Masri R, Driscoll CF, Romberg E. The change in retentive values of locator attachments and hader clips over time. J Prosthodont 2009; 18: 479-483.

19) Elsyad MA, Errabi HM, Mustafa AZ. Mandibular denture base deformation with Locator and ball attachments of implant-retained overdentures. J Prosthodont 2015: doi: 10.1111/jopr.12356. [Epub ahead of print].

20) Srinivasan M, Schimmel M, Badoud I, Ammann P, Herrmann FR, Maller F. Influence of implant angulation and cyclic dislodging on the retentive force of two different overdenture attachments - an in vitro study. Clin Oral Implants Res 2016; 27: 604-611.

21) Alsabeeha N, Atieh M, Swain MV, Payne AG. Attachment systems for mandibular single-implant overdentures: an in vitro retention force investigation on different designs. Int J Prosthodont 2010; 23: 160-166.

22) Matsushita Y, Kitoh M, Mizuta K, Ikeda H, Suetsugu T. Two-dimensional FEM analysis of hydroxyapatite implants: diameter effects on stress distribution. J Oral Implantol 1990; 16: 6-11.

23) 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.

24) Petrie CS, Williams JL. Comparative evaluation of implant designs: influence of diameter, length, and taper on strains in the alveolar crest. A three-dimensional finite-element analysis. Clin Oral Implants Res 2005; 16: 486-494.

25) Yu W, Yang JY, Kyung HM. Combined influence of implant diameter and alveolar ridge width on crestal bone stress: a quantitative approach. Int J Oral Maxillofac Implants 2009; 24: 88-95.

26) Baggi L, Cappelloni I, Di Girolamo M, Maceri F, Vairo G. The influence of implant diameter and length on stress distribution of osseointegrated implants related to crestal bone geometry: a three-dimensional finite element analysis. J Prostheth Dent 2008; 100: 422-431.

27) Kong L, Sun Y, Hu K, Li D, Hou R, Yang J, Liu B. Bivariate evaluation of cylinder implant diameter and length: a three-dimensional finite element analysis. J Prosthodont 2008; 17: 286-293.

28) Guan H, van Staden R, Loo YC, Johnson N, Ivanovski S, Meredith N. Influence of bone and dental implant parameters on stress distribution in the mandible: a finite element study. Int J Oral Maxillofac Implants 2009; 24: 866-876.

29) Iplikcioglu H, Akca K. Comparative evaluation of the effect of diameter, length and number of implants supporting three-unit fixed partial prostheses on stress distribution in the bone. J Dent 2002; 30: 41-46.

30) Elsyad MA, Al-Mahdy YF, Salloum MG, Elsaih EA. The effect of cantilevered bar length on strain around two implants supporting a mandibular overdenture. Int J Oral Maxillofac Implants 2013; 28: e143-150.

31) Takuhisa M, Matsushita Y, Koyano K. In vitro study of a mandibular implant overdenture retained with ball, magnet, or bar attachments: comparison of load transfer and denture stability. Int J Prosthodont 2003; 16: 128-134.

32) Gonda T, Ikebe K, Dong J, Nakube T. Effect of reinforcement on overdenture strain. J Dent Res 2007; 86: 667-671.

33) Elsyad MA, Elsadawwy MG, Abdou AM, Habib AA. Effect of different implant positions on strain developed around four implants supporting a mandibular overdenture with rigid telescopic copings. Quintessence Int 2013; 44: 679-686.

34) Akca K, Kokat AM, Sahin S, Iplikcioglu H, Cehreli MC. Effects of prosthesis design and impression techniques on human cortical bone strain around oral implants under load. Med Eng Phys 2009; 31: 758-763.

35) Porter JA, Jr, Petropoulos VC, Brunski JB. Comparison of load distribution for implant overdenture attachments. Int J Oral Maxillofac Implants 2002; 17: 651-662.

36) Heckmann SM, Winter W, Meyer M, Weber HP, Wichmann MG. Overdenture attachment selection and the loading of implant and denture-bearing area. Part 2: A methodical study using five types of attachment. Clin Oral Implants Res 2001; 12: 649-647.

37) Bedowsky SJ, Caputo AA. Stress transfer of four mandibular implant overdenture cantilever designs. J Prosthodont 2004; 92: 328-336.

38) Federick DR, Caputo AA. Effects of overdenture retention designs and implant orientations on load transfer characteristics. J Prosthodont 1996; 76: 624-632.

39) Coelho Goiato M, Pesqueira AA, Santos DM, Haddad MF, Moreno A. Photoelastic stress analysis in prosthetic implants of different diameters: mini, narrow, standard or wide. Journal of Clinical and Diagnostic Research : JCDR 2014; 8: ZC86-90.

40) Alsabeeha NH, Payne AG, De Silva RK, Thomson WM. Mandibular single-implant overdentures: preliminary results of a randomised-control trial on early loading with different implant diameters and attachment systems. Clin Oral Implants Res 2011; 22: 330-337.

41) Ketabi M, Deporter D, Atenauf BG. A systematic review of outcomes following immediate molar implant placement based on recently published studies. Clin Implant Dent Relat Res 2016, doi: 10.1111/cid.12390. [Epub ahead of print].

42) Chikunov I, Doan P, Vahidi F. Implant-retained partial overdenture with resilient attachments. J Prosthodont 2008; 17: 141-148.

43) Celik G, Uludag B. Photoelastic stress analysis of various retention mechanisms on 3-implant-retained mandibular overdentures. J Prosthodont 2007; 97: 229-235.

44) Enlow DH, Bianco HJ, Eklund S. The remodeling of the edentulous mandible. J Prosthodont 1976; 36: 685-693.

45) Sub JH, Shelemay A, Choi SH, Chai JK. Alveolar ridge splitting: a new microsaw technique. Int J Periodontics Restorative Dent 2005; 25: 165-171.

46) El-Sheikh AHM, Shihabudinn OF, Ghoraba SM. Two versus three narrow-diameter implants with locator attachments supporting mandibular overdentures: a two-year prospective study. Int J Dent 2012; 2012: 285684.

47) Gottfredsen K, Berglundh T, Lindhe J. Bone reactions adjacent to titanium implants subjected to static load of different duration. A study in the dog (III). Clin Oral Implants Res 2001; 12: 552-558.

48) Kitamura E, Stegaroiu R, Nomura S, Miyakawa O. Biomechanical aspects of marginal bone resorption around osseointegrated implants: considerations based on a three-dimensional finite element analysis. Clin Oral Implants Res 2004; 15: 401-412.

49) Ichikawa T, Horiuchi M, Wigianto R, Matsumoto N. In vitro study of mandibular implant-retained overdentures: the influence of stud attachments on load transfer to the implant and soft tissue. Int J Prosthodont 1996; 9: 384-389.

50) Hong HR, Pae A, Kim Y, Paek J, Kim HS, Kwon KR. Effect of implant position, angulation, and attachment height on peri-implant bone stress associated with mandibular two-implant overdentures: a finite element analysis. Int J Oral Maxillofac Implants 2012; 27: e69-76.

51) Akca K, Cehreli MC, Iplikcioglu 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.