Original Article

Three Dimensional Finite Element Analysis of Distal Abutment Stresses of Removable Partial Dentures with Different Retainer Designs

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Abstract
Objectives: This finite element method study aimed to compare the amount of stress on an isolated mandibular second premolar in two conventional reciprocal parallel interface designs of removable partial dentures (RPDs) and the same RPD abutment tooth (not isolated).
Materials and Methods: A Kennedy Class 1, modification 1 RPD framework was simulated on a 3D model of mandible with three different designs: an isolated tooth with a mesial rest, an isolated tooth with mesial and distal rests and an abutment with a mesial rest (which was not isolated); 26 N occlusal forces were exerted bilaterally on the first molar sites. Stress on the abutment teeth was analyzed using Cosmos Works 2009 Software.
Results: In all designs, the abutment tooth stress concentration was located in the buccal alveolar crest. In the first model, the von Mises stress distribution in the contact area of I-bar clasp and cervical portion of the tooth was 19 MPa and the maximum stress was 30 MPa. In the second model, the maximum von Mises stress distribution was 15 MPa in the cervical of the tooth. In the third model, the maximum von Mises stress was located in the cervical of the tooth and the distal proximal plate.
Conclusion: We recommend using both mesial and distal rests on the distal abutment teeth of distal extension RPDs. The abutment of an extension base RPD, which is not isolated in presence of its neighboring more anterior tooth, may have a better biomechanical prognosis.
Key Words: Finite Element Analysis; Abutment; Retainer
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INTRODUCTION

Many studies have been done on the design and stress distribution of removable partial dentures RPDs and abutment teeth using finite element method (FEM), strain gauges, and photo elastic techniques [1-15]. Appropriate design in a RPD is critical for proper force distribution and avoidance of excessive loading of the periodontal ligament (PDL) of the abutment tooth [1]. By splinting an isolated abutment (often termed a pier abutment or lone-standing tooth) to its anterior tooth with an appropriately constructed fixed partial denture (FPD), detrimental forces on abutment tooth will be minimized. However, these teeth may not be splinted with a FPD, due to the clinicians' tendency of not preparing an intact isolated abutment and its anterior tooth. There is little scientific evidence about the consequences and differences of splinting or not splinting isolated teeth [2-4].

Generally, dentists recommend that pier abutments not be clasped but may receive rests. However, the clinician should determine (on an individual basis) whether the patient would benefit from splinting an isolated tooth with a FPD or not [3]. In the dental community, there is no consensus in treatment planning for lone standing abutments. For example, a dentist choosing to place a direct retainer on a canine rather than a second premolar is considered to have made a poor choice from an esthetic viewpoint. However, if a dentist decides to clasp the second premolar (i.e. isolated tooth), his or her choice may lead to generation of potentially detrimental forces. In addition, the preparation of an intact canine and second premolar for a FPD is neither conservative nor cost-effective for patients, but will reduce force to the pier abutment.

In a Kennedy Class 2 design, use of a modification on the other side of the arch, even at the expense of keeping a pier abutment, improves prosthesis stability and retention. However, this abutment may be subject to torsional forces above its PDL's physiological tolerance. A mesial rest is one of the approved designs for reducing deleterious forces (generally resulting from denture base movement). The mesial rest can change the fulcrum line location and help direct the forces more vertically to the residual ridge. In addition, a more flexible retentive clasp (wrought wire) can be used for minimizing harmful forces to the pier abutment. Reciprocal parallel interface designed with a mesial rest, distal proximal plate, and I-bar clasp (positioned at or mesial to the mesiodistal height of contour) engages a 0.010-inch undercut [2,5].

The amount of torsional forces applied to abutments depends on the prosthesis design, quality of the bone and soft tissue of the residual ridge, extension of free-end denture base, and patient's muscular forces. Each abutment should be examined carefully for its bony support and previous bone reaction to occlusal stress [2]. Lack of consensus exists among different studies about the location of occlusal rest on the distal abutment tooth (either mesially or distally). The purpose of this 3D FEM study was to investigate the stress induced in the distal abutments of an I-bar-retained RPD in a mandibular bilateral distal extension partial denture where the distal pier abutments had varying locations of occlusal rests (either mesially or distally) and the other abutment was not isolated.

MATERIALS AND METHODS

Using pre-existing CT scan data obtained from a 24 year-old man's skull, a 3D mandibular model was fabricated. In the model, there was 1 to 2mm distance between CT section images. The data were transferred to Mimics software for simulation.

This software processes 3D images and converts CT data to 3D Computer Aided Design (CAD) models. In the modeling procedure, Mimics software was used to eliminate the first premolar on one side and first and second molars of both sides, so that the second premolar was isolated between the two edentulous areas. In this way, a Kennedy Class 1, modification 1 RPD was simulated in the mandible. By preparing Dicom films, Mimics software was used to isolate the trabecular bone, cortical bone and tooth crown with X-ray absorption coefficients of 100-300, 300-2000 and more than 2000, respectively.

Mimics software data were transferred to Solid Works 2009 (Structural Research & Analysis Corporation, CA, USA) for modeling and FEM analyses. Sockets of eliminated second premolars were filled with 18.5mm thickness cancellous bone and covered with 1.5mm thickness cortical bone.

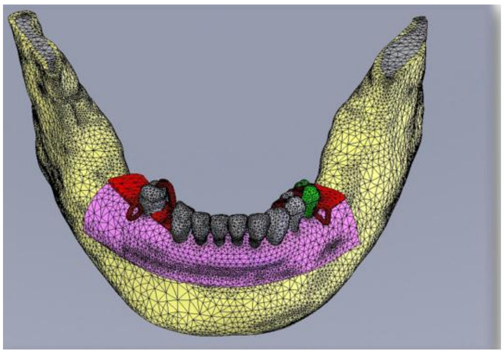

Fig. 1. Meshing of model 1 (yellow represents mandibular bone, red and pink show the RPD framework and acrylic resin, respectively).

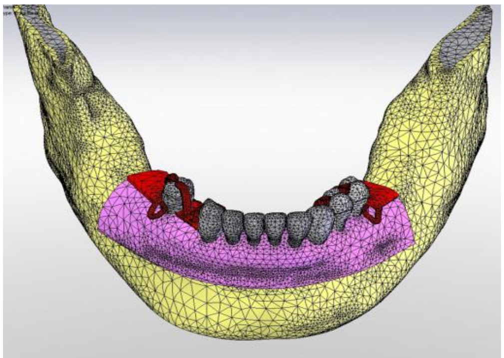

Fig. 2. Meshing of model 2.

A PDL with 0.25mm thickness was simulated around the tooth's root. All the materials used in this study were considered to be linearly elastic, homogenous and isotropic. Two different models were designed on this partially edentulous model with an isolated second premolar for comparison. In all models, a half-pear-shaped lingual bar with 5mm height and 2mm thickness, which allowed 3mm of space between the gingival margins and the superior border of the bar was constructed as the major connector. The reciprocal parallel interface (RPI) design, with an I-bar retentive clasp positioned in the mid-buccal undercut and a mesial rest, was designed for the isolated second premolar. The contact area between I-bar and abutment tooth was about 2mm in height and 1.5 to 2mm in width. The second model was identical to the first model, with the exception of just positioning two mesial and distal rests on the isolated second premolar. In the third model, the first premolar was not eliminated and there was no isolated tooth.

To compare stress concentration, other parts of the framework design were kept identical with the other two models such as the use of RPI design (Fig. 2).

The RPD frameworks were physiologically adjusted. Simulation was performed with a static analysis by using Cosmos Works 2009 software with which, boundary conditions and physical properties of different components were defined more accurately [6,16,17] (Table 1).

This contact area had a uniform taper throughout its length. The horizontal component of the I-bar was 4mm farther from the gingival margin. In the distal of the isolated tooth, the proximal plate was extended to the cervical one-third of the abutment. In the opposite side of the arch, mesial rests were designed for both first and second premolars (Fig. 1) [3].

Since the analysis was static, it was independent from loading time and all contact border conditions between all parts were considered equal.

Table 1. Materials' properties [6]

Material	Elastic modulus (MPa)	Poisson's ratio
Dentin	18600	0.31
Enamel [8]	83000	0.33
Periodontal ligament [7]	0.0689	0.45
Cortical bone	13700	0.30
Cancellous bone	1370	0.30
Ni-Cr alloys	200000	0.33
Denture base	4500	0.35
Mucosa	1	0.37

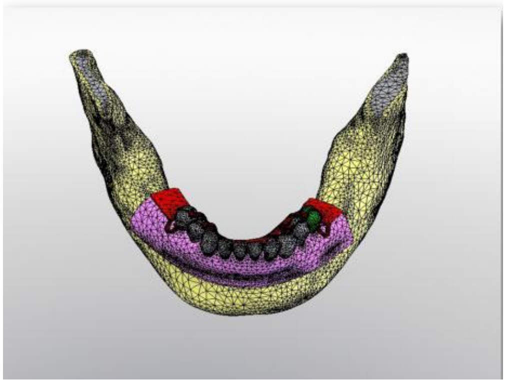

Fig. 3. Meshing of model 3 (the I-bar and the enamel surface are connected with a surface-to-surface connection)

Meshing was performed using a linear geometric and tetrahedral element shape. The mesh size was 1.5mm. In the PDL, contact elements with a node-to-node connection were used. The mesh size at the contact area (I-bar-tooth) should be small. Sharp edges, rest seats and force application surfaces are other critical areas to be considered as stress concentration sites. The mesh size was 1.5 mm and a total of 393,314 elements and 637,348 nodes were used in this model (Figs. 1-3).

Masseter and medial pterygoid muscles were considered as the main sites of application of masticatory forces. Simulated forces were applied vertically to the occlusal surface. The occlusal force exerted against the complete denture, FPD, and RPD varies considerably. On the RPD, it is about 25-26N [18, 19]. In this study, 26 N load was exerted bilaterally on the first-molar sites, about 13mm distal to the first premolar. The objective of this FEM study was to compare the amount of stress and probable movement of an isolated mandibular second premolar tooth in two conventional RPI designs of RPDs and the same RPD abutment tooth (which was not isolated).

RESULTS

In the first model (isolated second premolar with a mesial rest), the von Mises stress distribution at the contact area of I-bar clasp and cervical portion of tooth (from buccal and distobuccal views) was 19 MPa and the maximum stress generated in this area was 30 MPa (with a range of 12 to 22 MPa). In this model, the mean strain was 90 microstrains and the maximum strain was 1550 microstrains. In the distal proximal plate, the von Mises stress distribution was 13 MPa. In the mesial rest seat, the von Mises stress distribution was 30 MPa (with a range of 8 to 20 MPa). In the middle-third of the tooth, the von Mises stress distribution was 6.67 MPa. Maximum displacement in the cervical portion was toward the buccal (more than 500 microstrains). The maximum von Mises stress distribution around the buccal bone (surrounding isolated tooth) was about 3.3 MPa (with a range of 2 to 4 MPa). In the distobuccal area, the von Mises stress distribution was more than 5 MPa (Fig. 4). In the second model (isolated second premolar with both mesial and distal rests), the maximum von Mises stress distribution in the buccal was 15 MPa (with a range of 13 to 22 MPa) and was concentrated at the cervical of the tooth. Maximum stress distribution in the contact area of the I-bar clasp and cervical portion of the tooth was 30 MPa.

In the distal rest seat, the von Mises stress distribution was 12.5 MPa (which was much less distributed than the mesial rest seat with 17 MPa). In the distal proximal plate, the von Mises stress distribution was 11 MPa. Tooth displacement in the cervical portion was 400 microstrains toward the buccal, with a mean value of 70 and the maximum of 1,150 microstrains. The von Mises stress distribution around the bone (surrounding the isolated tooth from the buccal aspect) was 3 MPa, and the maximum stress was found in the distal alveolar bone crest and measured 5 MPa. In the third model (the abutment tooth which was not isolated), the maximum von Mises stress distribution was located in the cervical of the tooth (in the buccal) and also in the distal proximal plate. Stress distribution in the buccocervical region was 7MPa (with a range of 6.3 to 11.5 MPa).

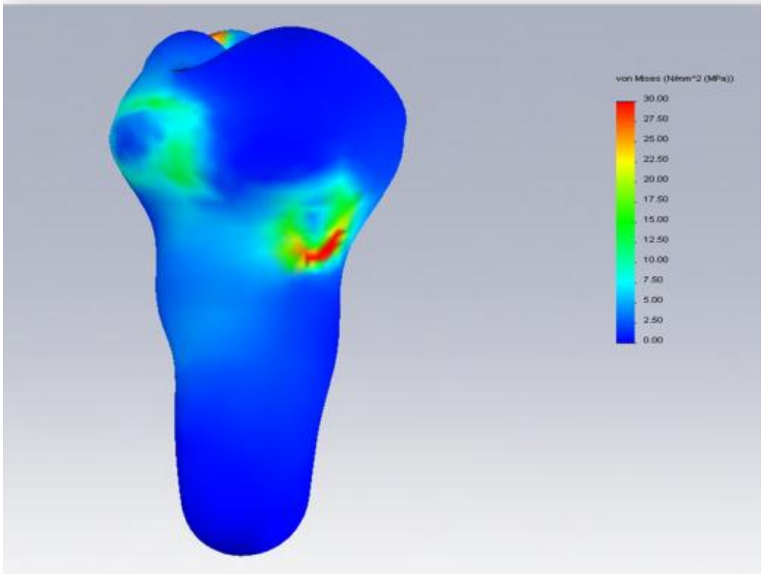

Fig. 4. Stress distribution in the isolated second premolar tooth in model 1 from the distobuccal aspect. The overall length of this tooth was 24 mm, with 15 mm root length and 9 mm crown length.

In the I-bar contact area, the stress distribution was about 15 MPa; this value in the distal proximal plate was about 8 MPa (with a range of 6.5 to 11 MPa).

Maximum stress distribution generated in the distal of the tooth was 15 MPa and was located around the contact borders of the proximal plate. Maximum stress distribution in the borders of the mesial rest was also 15 MPa (with a range of 6.8 to 11 MPa).

In the tooth root, from the cervical one-third to the middle-third, the maximum stress distribution was 3.8MPa (Table 2). The strain amount in the proximal plate of the second premolar was about 350 microstrains, and the maximum strain observed in this area was 700 microstrains. In this model, the maximum strain was 1,600 microstrains with a mean of 82 microstrains.

Stress distribution in the cervicobuccal region of the bone around this abutment tooth was 2.1 MPa, and the maximum stress was observed in the distal area (which was 5 MPa, with a wider range than lingual area).

DISCUSSION

In this study, the numerical values of the von Mises stress produced in different areas of mandibular second premolar abutments of RPDs with different retainer designs were evaluated using 3D FEM. During this evaluation, a static load was applied to underlying tissues in two different models with an isolated abutment and a model without a pier abutment. In consideration of the less bony support of mandibular teeth and preponderance of Kennedy Class 1 and 2 in RPD design, a Kennedy Class 1 mandibular model was prepared.

Table 2. The von Mises stress distribution in different areas of three models

Model \ Area	I-Bar Contact Area	Distal Proximal Plate	Distal Rest	Mesial Rest
1st Model	19 MPa	13 MPa	-	30 MPa
2nd Model	30 MPa	11 MPa	12.5 MPa	17 MPa
3rd Model	15 MPa	8 MPa	-	15 MPa

Generally, an identical situation for evaluating an abutment tooth can be obtained more easily through in vitro studies. Fernandes et al, in a study using strain gauges stated that in vitro models of maxillary RPDs are not suitable for accurate mechanical analysis. They further explained that in vitro studies can be useful only for simple determination of strain levels like our study [7]. A FEM is useful for assessing stress and strain levels in biomaterials and human tissues not easily measured by in vivo techniques [8]. As photoelastic techniques provide two-dimensional and qualitative information, these stress patterns should be analyzed carefully [9]. Fernandes et al, in a study compared reflective photoelasticity and strain and concluded that reflective photoelasticity has important advantages such as validity, reliability and ease of use; tests are not performed with a model (i.e. like FEM) and the object itself is used for reflective photoelasticity [10]. They explained that reflective photoelasticity has some limitations; for example, it should be restricted to in vivo studies of the anterior teeth because it requires the accessibility of directed light under clinical situations.

A further limitation is that reflective photoelasticity can only determine surface strain and direct loading of the coated surface should be avoided. Reflective photoelasticity is better used in combination with other analytical techniques such as strain gauges, in order to completely analyze mechanical conditions of prosthetic appliances under load application. In our study, as direct loading was applied 3D FEM was preferred over reflective photoelasticity in order to assess the abutment teeth. Strain gauge techniques can be useful only for point stress analysis; therefore, many gauges and difficult mathematical calculations are used [10]. Due to these limitations, we preferred to use 3D FEM in this study. All the materials used in this study were considered to be linearly elastic, homogenous, and isotropic.

Wakabayashi et al stated that the force-movement relationship of a tooth cannot be analyzed by a linear static model because this relationship is represented by a nonlinear curve. They stated that the linear static model should be used only in the studies measuring the difference of a tooth under limited range of load, like the current study. However, they stated that the validity and reliability of nonlinear FEM in dentistry have not been adequately reported [8]. McCartney in a clinical study explained that the clasp design has a direct influence on the direction and amount of transmitted force to abutment tooth [11]. Taylor et al indicated that tooth movement with a circumferential casting clasp is more than a RPI design, and that only with appropriately extended and adapted denture base, will the clasp changes be minimized [12]. In different studies on mandibular bilateral distal extension partial dentures, physiologically adjusted RPDs with an I-bar design and mesial occlusal rests have been recommended [4]. Aoda et al investigated the effect of three different retainer designs on loading of abutment teeth of a mandibular unilateral extension base RPD using 3D FEM. In all designs, the load on the second premolar, which was adjacent to the region of the missing teeth, was high, suggesting that almost the entire load was supported by the distal abutment. Akers' clasps positioned over the first and second premolars produced the largest load on the abutment teeth [13]. However, in our study I-bar design was used which is considered to cause less detrimental load on the distal abutment teeth, and the RPD frameworks were physiologically adjusted in all three models. Frechette explained the effects of RPD designs on force transfer to abutments. He concluded that the rest position, rigidity and contour of the major connecter and the amount of extension base may have an effect on the abutment movement [1]. In our study, maximum von Mises stress distributions in all three models were located in the I-bar placed in the buccocervical region of abutments, distal proximal plate and the middle third of the root. The stress magnitude and distribution in the mesial rest seat was more than the distal rest seat.

Maximum stress magnitude in model 1 (an isolated abutment with a mesial rest) was 38.9 MPa and in model 2 (the pier abutment with both mesial and distal rests) was 36.7 MPa. The mean stress in model 1 was 2 MPa and the mean stress in model 2 was 1.6 MPa.

Finite element analysis (FEA) is a numerical method in bioengineering and a valid method to predict and simulate different complex structures. By comparing these models, we found that the tooth movement in model 2 (with both mesial and distal rests) was less than the other two models. This finding may be a result of tooth engagement (in this model) with two rests and proximal plates. Muraki et al, in a FEA explained that mesially or distally positioned rest seats did not have a significant difference in abutment tooth movement. They stated that limiting horizontal rest movement in its seat (through precise fitness) may reduce abutment tooth movement in the horizontal dimension [14]. Under a similar assumption, we believe that less movement and strain in model 2 in our study (with both mesial and distal rests) may be justifiable. In our study, precise and firm fitness between all rests and rest seats in the three models was examined carefully. Muraki et al reported maximum tooth movement toward the buccal, which is similar to the result of our study [14]. Cecconi et al studied the effects of clasp design on abutment tooth movement. They explained that by placing either a mesial or distal rest, maximum abutment tooth movement occurred in the mesial and buccal direction [15]. We obtained the same result in our study. The stress distribution in the distocervical alveolar bone crest of the isolated tooth (in buccal) was more than in the lingual surface (which included sharp edges). Considering possible tooth movement toward the mesial and buccal (and the thinner buccal bone compared with the lingual bone), we believe that higher stress concentration in the buccal aspect is important. This issue is important to consider as it may result in increased bone resorption, pocket depth or tooth mobility.

The prognosis of the abutment tooth of RPD depends on the amount of periodontal pocket depth and its mobility.

Base adaptation, which reduces as a result of time-dependent bone resorption, may itself increase force intensity applied to abutments. Despite biomechanical factors, plaque accumulation and poor oral hygiene always aggravate these problems.

In a clinical study, Goodkind evaluated RPD consequences with regard to tooth mobility. They observed that premolar tooth mobility increased only toward the buccal and there was no statistical difference in tooth mobility toward the lingual. They explained this finding to be the result of the thin buccal bone compared to the thick lingual bone [20]. In a clinical study by Tebrock et al, tooth mobility also increased toward the buccal [21].

Tebrock et al explained that this result could be related to the lingual arm bracing [21]. In our study, the stress concentration in all models was located on the buccal side of the abutment and in the middle-third of its root. This result may be due to the rotational movement of tooth around a center point in the root toward the buccal, which is similar to the studies by Goodkind [20] and Tebrock et al [21]. Interestingly, tooth movement in model 3 was more than in model 2. However, according to the results of our study, tooth movement was toward the buccal, and strains generated in the bone of the abutment tooth did not seem to be more than the physiological tolerance threshold. In an in vitro study using strain gauge technique, el Charkawi et al designed a mandibular bilateral distal-extension RPD with a resilient layer and circumferential clasps on the distal abutments (the second premolars) [22]. They stated that strain gauge technique is an accurate, consistent and reproducible technique for in vitro studies of RPD designs. They used controlled load instead of static load by using an artificial oral environment (artificial mouth). In all three axes of motion, the lingual strains were relatively higher. They stated that it might be the result of RPD design factors such as circumferential clasp pressure [22]. Their result contradicts the findings of our study. In our study, von Mises stress in the buccal bone was more than in the lingual bone. Of course, they used Akers' clasp on the distal abutments, which is contraindicated especially in combination with resilient-layer distal extension because it would exert extra detrimental forces to the distal abutment [21]. Despite the identical situations in all three models of the current study, greater stress distribution was found in models 1 and 2 with isolated abutments than in model 3 without an isolated tooth. The maximum von Mises stress in models 1 and 2 was about 30 MPa. The range of maximum von Mises stress for model 3 was about 15 MPa.

This result can be explained by the existence of more anterior neighboring teeth and the continuity of the dental arch in model 3.

The movements of RPDs can occur in any of the three fundamental planes: horizontal, sagittal and frontal. The RPD movements include movements towards and away from the supporting ridge, and the mediolateral rotational movements that occur relative to the edentulous alveolar process. All these movements and resultant strains require intricate calculations that are too complicated for a single study. In our study (like most other in vitro RPD articles either using FEM or other methods), RPD movements that occurred toward the ridge were considered. The most dominant functional forces were applied around the molar regions, and these forces were considered in our study.

In our study, we only considered forces applied vertically to the occlusal surfaces and toward tissues. The mastication cycle does have other forces with different directions (for example away from tissues) [22].

We recommend further research and clinical studies in which an isolated tooth is used as an abutment for a FPD to compare it with other pier abutments either with or without a direct retainer of RPD.

Clasp assemblies with a different amount of proximal plate coverage can be designed in other studies.

CONCLUSION

Within the limitations of this study, the following conclusions were drawn:

1. Maximum stress distribution in all three models was at the cervicobuccal region of the tooth in the location of the I-bar retentive clasp, in distal guiding plane of the abutment, and the middle-third of the root.
2. In model 2, stress magnitude and distribution in the mesial rest seat was more than in the distal rest seat.
3. The von Mises stress distribution in model 1 was more than in model 2.
4. The von Mises stress distribution in models 1 and 2 with isolated tooth was much more than that in model 3.
5. In models 1 and 2, stress distribution was observed in the distocervical part of the alveolar bone crest surrounding the abutment.
6. The von Mises stress in the lingual bone was less distributed than in the buccal bone.
7. Maximum tooth movement in all three models was toward the buccal side. The tooth movement in model 2 with both mesial and distal rests was less than in models 1 and 3.

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