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Finite Element Method Analysis of Stress Distribution to Supporting Tissues in a Class IV Aramany Removable Partial Denture (Part II: Bone and Mucosal Membrane)

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Abstract

Aim: One of the most important issues in the design of removable partial dentures (RPD) is the location of retentive arms to provide sufficient support. This is a critical factor in patients with less supporting tissue and abutment teeth. Patients classified as Class IV Aramany need special attention in this area of RPD design to minimize the stress distribution in bone and mucosal membrane.

Using the finite element method, the aim of this study was to analyze the distribution stress to supporting tissues when a Class IV Aramany RPD is worn. The data presented in this report are the effects of the stress on bone and mucosal membranes. Results on teeth and the periodontal ligament have been previously reported.

Methods and Materials: Three dimensional finite element models were constructed using normal dimensions. Exact physiology and morphology of teeth and the remaining palate were simulated to that of a maxillectomy patient. Three RPD designs with circumferential cast retainers were examined: buccal retention and palatal reciprocation (P1); palatal retention and buccal reciprocation (P2); and buccal and palatal retention (P3). After completion of the models and remaining palate, each RPD design was loaded under 53N and stress was applied in three different directions: vertical to the posterior teeth (premolar and first molars) of the RPD (F1); at a 33^{o} angle to the posterior teeth (premolar and first molars) of the RPD (F2); and vertically on the anterior teeth (central incisors) of the RPD (F3).

The stress distribution in the RPD models on cortical and cancellous bone and the mucosal membrane was analyzed using von Mises criterion.

Results: The maximum tension in cortical bone (70.84 Mpa) was observed when a 53N force was applied in a vertical direction to posterior teeth (F2) using buccal and palatal retention (P3). Minimum tension (15.73 Mpa) in cortical bone was observed using the F3 load on the P2 design.

Similar results were seen in cancellous bone, with the highest stress (8.01 Mpa) observed using F2 load on the P3 design and the lowest stress (3.04 Mpa) observed using the F3 load on the P2 design.

For mucosal membrane, the maximum (3.57 Mpa) and minimum (3.05 Mpa) stress was observed using the F3 load on the P3 design and the F1 load on the P2 design, respectively. The average stress in all RPD designs was 3 Mpa.

Conclusion: The design demonstrating the least tension in cortical and cancellous bone and mucosal membrane was the P2 design, a RPD with palatal retention and buccal reciprocation.

Clinical Significance: Palatal retention and buccal reciprocation (P2 design) is recommended for patients with maxillofacial RPDs.

Keywords: Finite element method analysis, Aramany CL IV, removable partial denture, RPD

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Introduction

Rehabilitation of the maxillectomy defect has been well defined for prothodontists and surgeons.[1] A successful prosthetic design for functional restoration of the maxillectomy defect utilizes the remaining palate and dentition to maximize the support, stability, and retention of an obturator bulb in the design of the removable partial denture (RPD).[2] An unfavorable situation for prosthetic rehabilitation occurs when the size of a defect is so large it overwhelms the remaining structures that stabilize a prosthesis over the defect.

Aramany[3,4] proposed a defect classification system describing different mechanics recommended in the prosthetic design of an obturator framework for partially edentulous patients. The Aramany system is described as follows:

- Class 1, maxillectomy without an oro-antral fistula
- Class 2, low maxillectomy (not including orbital floor or contents)
- Class 3, high maxillectomy (involving orbital contents)
- Class 4, radical maxillectomy (includes orbital exenteration)

Classes 2 to 4 are qualified by adding the letter a, b, or c. The horizontal or palatal component is classified as follows: (a) unilateral alveolar maxillectomy; (b) bilateral alveolar maxillectomy; and (c) total alveolar maxillary resection.

A definitive obturator for partially edentulous patients has two main components: a metallic framework and an acrylic resin obturator bulb. The metallic framework is designed to stabilize anticipated cantilever force along the fulcrum line defined by terminal abutment.[5] The remaining palate and the dental arch are integral to the stability of the prosthesis. Important considerations in the design of the framework are the size and location of the defect. The stabilization of the obturator bulb and its intimacy with the soft tissues that line and surround the defect are thought to minimize adverse effects

such as nasal leakage and hypernasal speech.[2] Every effort should be made to re-establish a favorable distribution of force to achieve stabilization of an obturator prosthesis during mastication and function.

The three dimensional finite element method of analysis has been commonly used to estimate the stress distribution within the hard and soft tissues. However, most of these models are linear elastic. Sliding and friction phenomena that may occur between a prosthesis and an abutment tooth, bone, or soft tissue have not been adequately analyzed by three dimensional models. These problems can be partially solved by non-linear contact analysis.[6]

In a review of stress distribution Frechette described three major schools of thought which influence practical procedures in the planning and construction of partial dentures.[7] One utilizes stress breakers as a means of loading the tissues selectively; the second equalizes the stresses between teeth and ridge through functional loading of the denture; and the third looks to broaden the distribution of the forces to prevent tissue overloads.

In a maxillectomy partial denture, Class I Aramany, with different designs, three dimensional photo elastic analyses of stress distribution to tissues and teeth showed there was a significant decrease in the stress on supporting tissues after physiologic adjustment of partial frames, and the greatest amount of stress was observed in the premolar area.[8,9]

Little research exists about the behavior of different designs of RPD in the Class IV Aramany patient with regard to stress on bone and mucous membrane. The present study was conducted under laboratory conditions to determine the effect of three different partial denture designs and their response to three different directions of force load on the stress distribution of a RPD designed for a radical maxillectomy (including orbital exenteration) or Class IV Aramany.

Methods and Materials

The Computer Model

The methods and materials have been previously described by Gharechahi et al.[10] Briefly, using Auto-CAD® (Autodesk Development Sarl, Neuchâtel, Switzerland) and Adobe Photoshop® (Adobe Systems Inc., San Jose, CA, USA) software a computerized anatomical model of the teeth and supporting tissues was created. Normal dimensions and morphological features of first and second premolars and first and second molars were constructed.[11] Bone and supporting tissue characteristics were derived[12-13] and used as a model for maxillectomy patients.

The alignment of teeth in the jaw and position of the teeth according to a longitudinal axis was considered in the computer model. Specific pathways and similar undercuts in the end of retentive arms of the metal framework were also considered in the computer model. After modeling of teeth and their alignment, the periodontal ligament (PDL) with a 0.25 mm thickness was designed around the roots. The normal thickness of the palatal vault (1.5 mm) was constructed on palate. Buccal maxillary walls were created according to the surface layer of the bone and consisted of cortical bone and the inner layers of cancellous bone. The data were then transferred to the computer. Characteristics of a Class IV Aramany RPD (palatal plate, minor connector, guiding plate, rests, retentive and stabilizing arms) were replicated in the model.[11,14]

Partial Denture Designs

P1: Circumferential cast retainer with buccal retention and palatal reciprocation.

- The maxillary major connector was a palatal plate with embrasure clasps put on the first and second premolars and on the first and second molars. The embrasure clasp consisted of a rest on mesial of the second molar and distal of the first molar. The retentive arm of the embrasure clasp was constructed on the buccal aspect and the stabilizer arm on palatal surface.

P2: Circumferential cast retainer with palatal retention and buccal reciprocation.

- Similar to P1 in respect to the major connector, rest seats and clasp design except for the retentive arms of embrasure clasps were on palatal surface and the stabilizer arm on the buccal aspect.

P3: Circumferential cast retainer with buccal and palatal retention.

- Similar to P1 except the two embrasure clasps were used as retentive arms.

Young's Modulus and Poisson's ratio of cancellous and cortical bone, dentin, enamel, PDL, mucosa, and chrome cobalt alloy were entered in the program to simulate a tooth and supporting tissues (Table 1).

Force Application

The stress distribution in computer models using the von Mises criteria was analyzed for each RPD design when placed under a 53N load applied by the software using the finite element method, the same as it is in the mouth during mastication from three different directions that included the following:

- F1 = vertical to the posterior teeth of the RPD
- F2 = at a 33° angle to the posterior teeth of the RPD
- F3 = vertically on the anterior teeth of the RPD

Analytical Software

The prepared models were assembled with solid elements and analyzed with ANSYS, version 5.4 (ANSYS Europe Ltd., Abingdon, UK) software for stress distribution. In this study the von Mises criteria was used for comparing stress distribution patterns on RPD supporting tissues (cancellous and cortical bone and mucosal membrane) (Table 2).

Results

Results were displayed showing all dimensions and colored pictures. von Mises tension pattern images were used to evaluate the results (Figures 1A and B).

Results of the nine configurations: three RPD designs, P1-P3, and the three force directions applied, F1-F3, are shown numerically by Mpa in Tables 3 to 5.

The maximum tension in cortical bone (70.84 Mpa) was observed when a 53N force was applied in a vertical direction to posterior teeth (F2) using buccal and palatal retention (P3).

Table 1. Poisson index and modulus of elasticity of elements.

Material	Poisson Index	Modulus of Elasticity (Mpa)
Dentin	0.30	1.86×10^4
Enamel	0.30	80×10^3
PDL	0.45	6.89×10
Cortical bone	0.30	1.37×10^4
Cancellous bone	0.30	1.37×10^3
Mucosal membrane	0.45	0.345×10
Chrome cobalt alloy	0.33	2069×10^3

Table 2. Elements in the design models.

Studied Models	Number of Elements	Number of Nodes
Buccal retentive clasp and palatal stabilizer (P1)	31807	61077
Palatal retentive clasp and buccal stabilizer (P2)	31863	62005
Retentive clasps on both sides of tooth (P3)	32041	63571

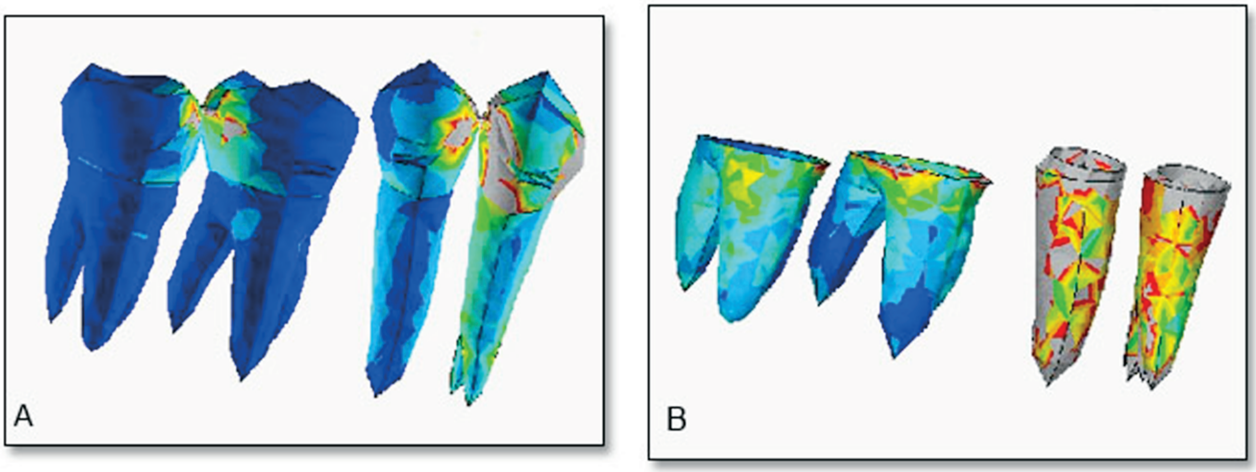

Figure 1. Stress distribution pattern in the P3 design. **A.** The teeth. **B.** The PDL.

Table 3. Maximum tension on cortical bone (Mpa).

Cortical Bone	F1	F2	F3
(P1)	55.44	60.28	61.41
(P2)	50.69	54.79	15.73
(P3)	70.14	70.84	17.47

Table 4. Maximum tension on cancellous bone (Mpa).

Cancellous Bone	F1	F2	F3
(P1)	5.76	6.27	3.35
(P2)	5.35	5.54	3.04
(P3)	7.42	8.01	4.29

Table 5. Maximum tension on mucosal membrane (Mpa).

Mucosal Membrane	F1	F2	F3
(P1)	3.10	3.14	3.52
(P2)	3.05	3.08	3.49
(P3)	3.13	3.19	3.57

Minimum tension (15.73 Mpa) in cortical bone was observed using the 53N load on the P2 design.

Similar results were seen in cancellous bone with the highest stress (8.01 Mpa) observed using F2 load on the P3 design and the lowest stress (3.04 Mpa) observed using the F3 load on the P2 design.

For the mucosal membrane, the maximum (3.57 Mpa) and minimum (3.05 Mpa) stress was observed using the F3 load on the P3 design and the F1 load on the P2 design, respectively. The average stress in all RPD designs was 3 Mpa.

Discussion

Finite element method analysis in maxillofacial prostheses has been used rarely because of the time involved and the difficulty of modeling. There is also little research on tension distribution of maxillofacial prostheses most of which have used the photoelastic method. As there has not been a general analysis on the pattern and amount of tension distribution in partial dentures of Class IV Aramany dentures, this study used finite element analysis to study the tension on the supporting tissues. In this study, three treatment options for these patients were studied under three different 53N force applications.

F1. Vertical Force Posterior Teeth

Cortical Bone. The area of maximum tension in this case was wider in the P3 design and was greater than the other two designs, P1 and P2. This area of maximum tension was found near the defect in the posterior part and continued towards the anterior of palate, due to the variability of rotation axis in these dentures. This was also reported by Donald and Myers.[9] Because of the resiliency of the mucosa and other underlying tissues, when force was applied to the denture, its rotation axis was transferred to deeper parts of the palate. The precise location of this rotation axis varies according to the design of the denture and amount and direction of force. In a comparison between the two RPD designs (P1 and P2), the area of maximum tension is similar but the amount of maximum tension in cortical bone was less in the P2 design compared with the P1 design. Maximum tension in this case was greater in P3 than the other two designs. P1 had less tension than P2, and P2 showed the least tension in cortical bone.

Cancellous Bone. The maximum tension and maximum tension area was observed in the P3 design. When the tension pattern of P1 and P2 were compared, the area of tension was similar for both, but the maximum tension in P2 was less than the P1 RPD design.

The general pattern of tension distribution in cancellous bone was similar to cortical bone but with a wider area and less maximum tension, possibly related to the low modulus of elasticity of cancellous bone and its greater mass compared to cortical bone.

Mucosal Membrane. The area of maximum tension was similar in all the three designs, P1, P2, and P3. This finding showed in a healthy mucosa with adequate thickness; there was no difference in stress tension from different retentive clasps on the mucosa.

F2. Force at 33° Angle to the Posterior Teeth

Cortical Bone. The maximum tension area in P3 design was wider than the other two designs, P1 and P2, and included the middle residual palate. P1 and P2 had similar maximum tension areas. But the maximum tension on cortical bone was higher in the P1 denture, leading to greater tension on teeth compared to the P2 denture.

The rotation concentrates in movement toward the tissue near the defect, therefore, presence of maximum tension in this area is not unpredictable, because of the resiliency of mucosal membrane. RPDs can be compressed in the movement toward the tissue. The rotation axis changes near the defect area interiorly towards the palate which defines the tension distribution in the interior parts of the palate.

The rotation axis movement was also studied by Donald and Myers on Class I Aramany patients and showed similar results.[9] It has also been shown when forces were applied obliquely on dentures, the area of maximum tension on supporting tissues was wider than vertical forces on the denture. In the present study the general pattern of tension distribution was similar with both 53N forces being applied vertically or at a 33º angle, but the area of maximum tension and the amount of maximum tension was greater with the 33º angle and wider than the vertical force. Maximum tension was greater in P3, and P2 showed the least tension. Findings of this study agree with the results reported by Beumer et al.[8]

Cancellous Bone. The pattern of stress distribution showed maximum tension in cancellous bone in the P3 design which continued from the defect area to the midpalate and near the palatal walls. The pattern of tension distribution was similar to cortical bone but because of the low modulus of elasticity and lower bulk of cancellous bone the maximum tension in cancellous bone was less than cortical bone. The area of maximum tension in cancellous bone was wider in the P3 design, leading to the maximum tension in cancellous bone. The area of maximum tension was similar in all three designs, but the maximum tension in P1 is more than P2 so the tension in cancellous bone was greater with P1 compared to P2. The maximum tension in cancellous bone is greatest with the P3 design and least in the P2 denture.

Mucosal Membrane. Similar areas and amounts of maximum tension were found in the mucosal membrane in all three RPD designs. It can be deduced if adequate thickness of mucosal membrane is present (1.5-2 mm) and has good support and connection with underlying bone, then similar tension is found with different denture designs.

F3. Vertical Force to Anterior Teeth

Cortical Bone. The area and amount of maximum tension in cortical bone in this case is wider in the P3 denture. This area of maximum tension was in an anterior area near the defect, medial to the border which occurred because of the movement of tissues after applying force. This study showed the area of maximum tension in P1 was wider than P2. In this situation the P3 design created the most tension, and the least tension was made by the P2 design.

Cancellous Bone. The general pattern of tension distribution in cancellous bone in this case was similar to cortical bone. The area of maximum tension was located in the anterior teeth and, by intimacy to the posterior section, maximum tension was reduced. The area of maximum tension was wider in the P3 design and the maximum tension made in this situation was greater. The maximum tension in P2 was less than P1. As a result, P3 made the greatest tension in cancellous bone and the P2 design created the least tension. The maximum tension in cancellous and cortical bone was the least when the force was applied on anterior teeth (F3). In F3, force was applied on the anterior residual palate and residual palatal walls so it was extended in a wide area. Therefore, little tension was made in cortical and cancellous bone. The length of movable level in F3 was shorter than the other two types because in this case force was applied to anterior teeth, and the distance between these teeth and anterior wall of the defect was less than the distance between posterior teeth and defect wall, therefore, magnitude of load and tension was low.

Mucosal Membrane. The pattern of tension distribution on mucosal membranes when force is applied on anterior teeth is different from the other two types of force application, F1 and F2. The area of maximum tension was on the anterior border of the defect and by nearing the posterior region the amount of tension was decreased. The exact location of the rotation axis was slightly medial to the border of the defect because of the resiliency of mucosal membrane. This is in agreement with Donald and Myers[9] who found the rotation axis in these dentures to be dynamic and its location is affected by design of denture and the amount and direction of force. All three denture designs under 53N force on anterior teeth showed similar area and amount of maximum tension.

Conclusion

Within the limits of this study, the following conclusions can be made from the findings:

1. In cortical bone maximum tension (70.84 Mpa) was observed in the P3 design with F2 force and minimum tension (15.73 Mpa) in the P2 design – with F3 force.
2. In cancellous bone the highest stress (8.01 Mpa) was observed in the P3 design with F2 force applied and the lowest stress (3.04 Mpa) in the P2 design with F3 force applied.
3. For mucosal membrane, the maximum (3.57 Mpa) and minimum (3.05 Mpa) stress was shown in the P3 design with F3 force applied and the P2 design with F1 force applied respectively, while the average of the stress in all situations was in 3 Mpa.

Clinical Significance

Palatal retention and buccal reciprocation (P2 design) is recommended for patients with maxillofacial RPDs.

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