Original Article

Evaluation of stress on the periodontium induced by a fixed retraction screw appliance and an active tie-back: A 3-dimensional finite element study

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Abstract

Objectives: To evaluate the stresses and displacement induced in the periodontium by an active retraction screw device (hycon device) and an active tie back using the finite element analysis. **Materials and Methods:** A 3-dimensional model of the maxillary dentition was designed for the study. A retraction force of 410 and 200 g was applied to simulate the forces generated by the hycon device and an active tie back respectively. The stresses generated by these forces were evaluated on the periodontium at cervix, mid root and apical region. **Results:** In the present study, maximum amount of tensile stresses were found on the labio-cervical (0.4919 and 0.2945 MPa) aspects of canine, compressive stresses on the linguo-cervical (−0.1758 and −0.0679 MPa) aspect of the 2nd premolar and the apical region of all teeth showed low magnitude compressive stresses, with both the loads. The displacement produced by the retraction screw was of the magnitude 0.172-0.183 mm (0.177 mm) in the anterior segment and 0.0065-0.007822 mm (0.0071 mm) in the posteriors (anchor loss). Active tie backs produce a displacement of 0.162-0.172 mm in the anterior segment and a negligible amount of displacement in the posteriors. **Conclusions:** Even though the stress level in the periodontium produced by hycon device was almost 2-3 times that of active tie backs, the displacement produced per activation was within the physiological limits and less than the width of the periodontium (0.20-0.25 mm), which in turn induces bone remodeling.

Key words: Active tie backs, finite element analysis, hycon device, repetitive active loading, retraction mechanics

INTRODUCTION

Orthodontic space closure has always been a challenge for the orthodontist. In fixed appliances it is achieved either by segmental retraction i.e., two step, involving canine retraction followed by incisor retraction[1,2] or single step, en-masse sliding technique involving retraction of all six anteriors at a time.[3,4]

With the advent of pre adjusted edgewise appliances, sliding mechanics has become the more preferred method and is accomplished using elastomeric chain, nickel titanium coil springs, active tie backs, intra-oral elastics, etc.[5,6]

Quinn and Yoshikawa[7] proposed four possible hypotheses for the relation between force magnitude and the rate of orthodontic tooth movement. The concept of optimum force levels for orthodontic tooth movement states that it should be just high enough to stimulate cellular activity without completely occluding blood vessels in the periodontal ligament (PDL).[8,9] Otherwise a hyalinized

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avascular necrotic area is formed, resulting in slow treatment progress and increased treatment time.[8] Most of the authors have thus recommended a force of 100-200 g during retraction irrespective of the technique.[10] All the above options have produced space closure of the magnitude of 0.5-1 mm/month.[6]

In sliding mechanics, friction occurs at the wire-bracket interface.[11] Studies have been carried out to evaluate frictional forces produced by various wire and bracket combinations.[12,13] Friction dissipates some of the applied force and decreases the rate of the tooth movement. Application of high magnitude force, in an attempt to overcome the friction, might increase the movement of the anchor teeth, and the belief has been that friction is detrimental to anchorage.[14] Studies have revealed that friction has no significant effect on the movement ratio of canine and anchor teeth, in two step retraction.[15,16]

Another important component is the frequency of applied force that has been neglected completely. Studies on rapid canine distraction have shown that repetitive activation expresses a favorable cellular response leading to rapid tooth movement.[17,18] With every activation, there is an up-regulation of the various factors (interleukins [IL], prostaglandins etc.) associated with the remodeling process within the PDL.[19,20] Research has proved that multiple cycles of change in force magnitude are significant in that bone and cartilage cells respond more readily to rapid oscillation in force magnitude than to a constant force.[20,21]

Recently, an alternative method of space closure has been proposed using an active retraction screw device (hycon device).[21] It consists of a retraction screw which allows precise closing activations at a relatively high force level, but over a short distance allowing reactivation more frequently for a more physiologic space closure.

In the present study, 3-dimensional finite element modeling (3D FEM) method was used to investigate the response of the maxillary anterior teeth to forces delivered by two retraction devices hycon appliance and active tie back in 3D, the stress developed in the periodontium and the amount of tooth movement achieved.

MATERIALS AND METHODS

The present analytical model was developed from a dried adult human skull with intact maxillary teeth and without any gross defects or discontinuity in the anatomy. Computed tomographic scan images of the maxillary dentition and supporting structures were made in the axial direction at 2 mm intervals in the horizontal plane. The dental and skeletal components were traced on acetate paper enlarged 140 times to the original skull size. This was traced onto a graph paper for digitization of x, y and z co-ordinates by using Microsoft Image Pro-plus software (Media Cybernetics, Inc., Rockville, MD, USA) (Image-Pro Plus image analysis software makes it easy to acquire images, count, measure and classify objects, and automate the work). These tracings were later imported into the AutoCAD engineering software version 2004 (Autodesk Inc., SanRafael, CA, USA) for modeling of the maxillary dentition with periodontium and bone which was saved in integrated graphics exchange system (.iges) format.

Finite element model generation was achieved with Altair Hypermeshversion7 (Altair Engineering Inc. Troy, Mich, USA) by converting the. .iges into .hm (hypermesh binary database files) format. The model was later converted into mesh diagram, boundary conditions applied and equation resolved using FEM and post-processing software (FEMAP - is CAD-independent Windows-native pre- and post-processor for advanced engineering finite element analysis) (SIEMENS: NEi Nastran Software Inc., Westminister, CA) run on a personal computer using the graphic accelerator.

The complete geometry is defined as an assemblage of discrete pieces called elements, which are connected to adjacent elements with the help of nodes, which joins them in all directions [Figure 1]. The total number of elements and nodes created were 45037 and 225400 respectively.

The material data used in this study were defined according to experimental data obtained from previous studies[22,23] [Table 1]. The FEM model was restrained in the inferior portion so that the teeth moved through the periodontium and bone without interference. The final FEM model was constructed in such a way that the dimensions of skull and

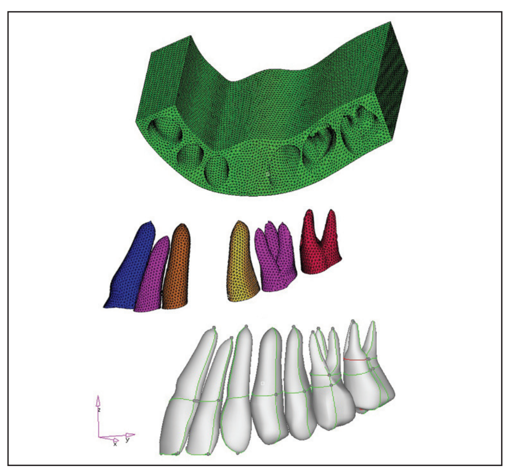

Figure 1: Completed finite element model of maxillary dentition with the periodontal ligament and alveolar bone

teeth matched average anatomical values. The maxillary dentition was consolidated into a separate unit consisting of all teeth except for 1st premolar [Figure 1], thus simulated the clinical scenario of therapeutic 1st premolar extraction. The forces generated by hycon device and active tie back were 400 g and 200 g respectively applied along the arch wire in the horizontal direction so as to simulate the retraction of maxillary anterior teeth with hycon device and active tie backs as in the 1st premolar extraction case [Figures 2 and 3]. The stresses on the periodontium were evaluated at three levels: The cervix, mid root and at the apex. The stresses were further evaluated on the labial, lingual, mesial and distal aspect at each level on all the teeth.

Table 1: Material constants of tooth, bone and periodontium

Material	Young's modulus (kg/mm²)	Poisson's ratio
Tooth	2.0×10^3	0.15
Alveolar bone	1.4×10^3	0.15
Periodontium	6.8×10^{-2}	0.49
Stainless steel	1.79×10^3	0.25

RESULTS

The biomechanical changes evaluated included stresses (compressive and tensile) — as principal stresses (maximum, moderate and minimum), Von Mises stress and displacements.

Von Mises is a theoretical measure of stress used to estimate yield failure criteria in ductile materials and is also popular in fatigue strength calculations (where it is signed positive or negative according to the dominant Principal stress), whilst Principal stress is a more "real" and directly measurable stress.

Only maximum principal stresses were used to describe the results as the moderated and minimal stresses produced negligible changes.

Maximum principal stress distribution

The pattern of stress distribution differed in various aspects (labial, lingual, mesial and distal) and at different levels (cervix, midroot and apex) of all maxillary teeth [Table 2]. This variation in stress distribution was induced by the

Table 2: Stresses on periodontium produced by retraction screw device and active tie backs

Teeth	Central		Lateral		Canine		2nd premolar		1st molar		2nd molar	
	410 g	200 g	410 g	200 g	410 g	200 g	410 g	200 g	410 g	200 g	410 g	200 g
Cervix												
Labial	0.008885	0.00223	0.09422	0.048	0.4919	0.2945	0.08309	0.04245	0.03954	0.01977	0.01049	0.00695
Lingual	−0.00526	−0.00288	−0.01039	−0.00533	−0.01419	−0.0071	−0.1758	−0.0679	−0.04024	−0.0284	−0.0417	−0.03895
Mesial	0.001292	0.000646	0.01128	0.00564	0.2789	0.1345	−0.02284	−0.01142	−0.1596	−0.0724	−0.02189	−0.01495
Distal	−0.01379	−0.0071	−0.01779	−0.00869	−0.0254	−0.0138	0.3746	0.1873	0.05012	0.02506	0.04335	0.021675
Middle												
Labial	0.00729	0.003845	0.02951	0.0215	0.02228	0.0166	0.01266	0.00656	0.01468	0.00734	0.008851	0.004426
Lingual	−0.00361	−0.0019	−0.00505	−0.00267	−0.01384	−0.00692	−0.02996	−0.015	−0.01513	−0.00648	−0.00619	−0.0031
Mesial	0.001942	0.000997	0.01117	0.00545	0.0217	0.0135	−0.01666	−0.00833	−0.02663	−0.0151	−0.01152	−0.00576
Distal	−0.0073	−0.0038	−0.02159	−0.012	−0.01476	−0.00788	0.02845	0.0179	0.01331	0.006655	0.003845	0.001883
Apex	−0.00414	−0.00202	−0.01199	−0.00585	−0.0111	−0.00572	−0.01196	−0.00583	−0.00953	−0.00477	−0.00357	−0.00139

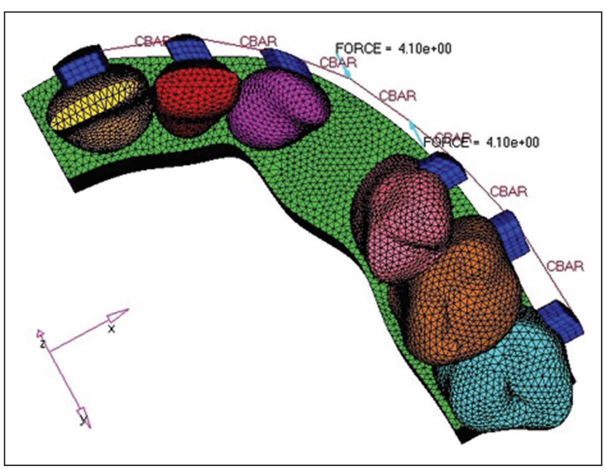

Figure 2: Clinical and numerical simulation of anterior segmental retraction with hycon

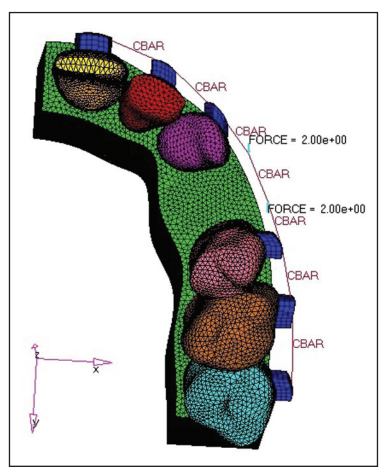

Figure 3: Clinical and numerical simulation of anterior segmental retraction with active tie backs

retraction devices-hycon device (410 g) and active tie back on the numerically simulated 3D FEM model of maxillary dentition [Figures 4 and 5].

The principal stress examined in the maxillary dentition demonstrated maximum amount of tensile stress on the labio-cervical and mesio-cervical aspect of canine and distocervical aspect of the 2nd premolar [Table 2]. This was seen in both types of retraction devices used in the study [Figures 4 and 5]. Labio-cervical aspect of maxillary central and lateral incisor also experienced maximum tensile stress as compared to other aspects. The disto-cervical aspect of the 1st and 2nd molar experienced low tensile stress, this was contrary to the observation in the 2nd premolar [Table 2]. Maximum compressive stresses were reported in the linguo-cervical aspect of the 2nd premolar and mesio-cervical aspect of 1st molar. However the apex of all teeth demonstrated minimal compressive stress [Figures 4, and 5 and Table 2]. In the maxillary anterior segment maximum compressive stress was induced in the disto-cervical and distal midroot region of central and lateral incisor, the canines however experienced maximum compressive stress in the linguo-cervical aspect [Table 2].

Displacement

The anterior and posterior segments were displaced in the backward and forward direction respectively in both types of retraction devices [Figure 6]. In the present study, the displacement produced by the hycon device was of the magnitude of 0.172-0.183 mm (0.177 mm) in the anterior segment and 0.0065-0.007822 mm (0.0071 mm) in the posteriors (anchor loss). Active tie backs produce a displacement of 0.162-0.172 mm in the anterior segment and a negligible amount of displacement in the posteriors.

DISCUSSION

In clinical practice, space closure is attained by the application of forces.[5-9] It has been realized from previous studies that the stresses generated in response to these forces vary with different methods and in different patients.[5-9,21,24] In the present study, retraction forces of 410 g with hycon device and 200 g with active tie backs were simulated and stress generated in the periodontium with these were analyzed on each tooth in all 3D of space at the cervix, midroot and apex. The maxillary 1st premolar was excluded from the model for the stimulation of the clinical situation of retraction in therapeutic first premolar extraction. Evidence from previous frictional studies suggested lesser magnitude of friction in 0.019 × 0.025” stainless steel (SS) wire than 0.021 ×0.025” SS wire.[25] Therefore, simulation in the present model was done with

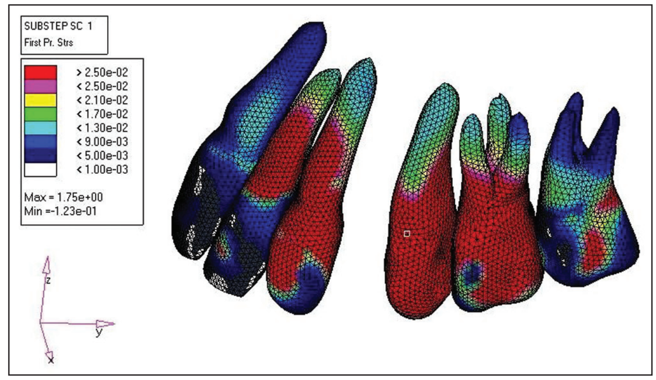

Figure 4: Principle stress at 410 g force using hycon device

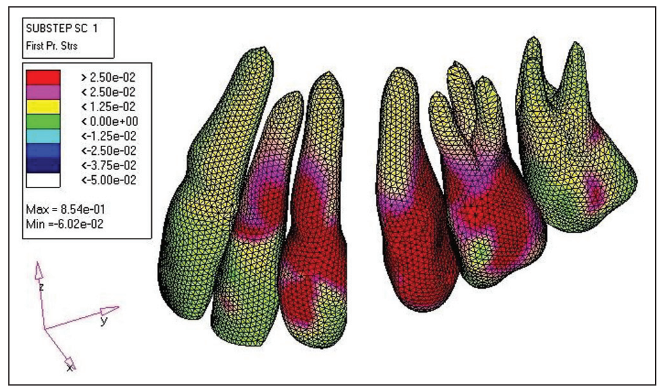

Figure 5: Principle stress at 200 g force using active tie backs

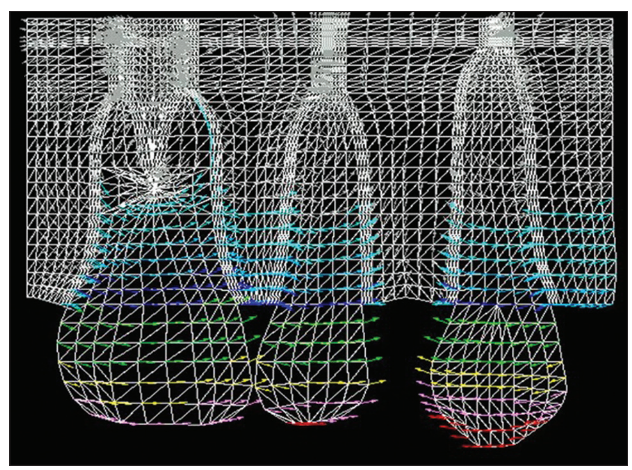

Figure 6: Displacement vector diagram

0.019 × 0.025” SS wire.

Over the years, too much emphasis has been placed on the magnitude of forces without considering the impact of frequency of forces on the biologic system.[5-7,22,24,26] Therefore, a simple retraction screw (hycon device) was chosen to facilitate precise repetitive activation to be carried out. The screw has a pitch of 0.35 mm that was determined by using the pitch gauge and by viewing and measuring it in a stereomicroscope at ×40 magnification. This was in conformation with the findings of McLaughlin *et al*.[21] Space closure typically occurs anterior and posterior to the periodontal space, which has been measured at 0.25 mm. Thus when the screw is turned 360°, it produces an activation of 0.35 mm and the activation for each tooth is about 0.175 mm, which is less than the periodontal space. The manufacturer recommends activation of the device by one turn twice a week. However, it was hypothesized that 2 turns in a week would probably squeeze the PDL and would not allow sufficient time for the periodontal tissues to recover. Thus, for this study, an activation of one turn/week was considered as a standard activation.

Stress distribution

FEM is a powerful contemporary research tool and it has been used as an analytical model with standard shape and mechanical behavior to estimate stress distribution in PDL.[22,27,30] Therefore, the results obtained provide insight into the stress generated in the periodontium of each maxillary tooth in all 3D of space at the cervix, midroot and apex, during the en-mass anterior retraction by both kinds of retraction devices (hycon device and active tie back) [Figures 4 and 5].

Earlier studies on stress distribution have shows that it varies with different kinds of tooth movement.[22,26, 3133] Authors have demonstrated that stress is uniformly distributed during the translation while during tipping there was greater stress in the cervix and the apex.[34] Our findings are discordant with the above observation. The principal stress was the least in the apex of the tooth but maximum tensile stress were reported in the mesio cervical and disto cervical aspect of canine and disto cervical aspect of 2nd premolar. This finding could be corroborated from the fact that the present model simulated en-masse anterior retraction in the 1st premolar extraction case. This may have contributed to greater stretching of the PDL fibers mesial and distal to canine and 2nd premolar respectively. Nevertheless, there is lack of evidence to support this finding.

As shown in Table 2, the principal stress distribution suggested higher stress to be generated during retraction by hycon device. Though, the stresses were 3 times higher in hycon screw device but were short lived and needed repetitive loading at shorter intervals to effect tooth movement when compared with an active tie back, which cause a constant force for a longer period of time. Studies on rapid canine distraction have shown repetitive activation to express a favorable cellular response leading to increased vascularisation and bone remodeling thus facilitating faster tooth movement. This has been supported by Lee *et al*.,[9] who demonstrated, that timely reactivation with appropriate forces might be capable of effective up-regulation of IL-1β, consequently having a great deal of influence on individual osteoclast-osteoblast differentiation cycle. Experimental study by Carano and Siciliani [20] suggests that a new mechanical stimulus is necessary to induce a new biological reaction. Mao and Nah[19] have also demonstrated that bone and cartilage cells respond more readily to rapid oscillation in force magnitude than to a constant force. Thus, it can be concluded that sequential repetitive loading of the PDL by weekly activation is beneficial in achieving a favorable cellular response and up-regulation of various markers that are involved during the anabolic and catabolic remodeling activities that occur during tooth movement.

Displacement

Orthodontic space closure varied from 0.5 to 1 mm/month attained by various methods.[6] Previous studies have reported that force is not decisive in determining the rate of bodily tooth movement.[35] In the present study, the displacement produced by the retraction screw was in the range of 0.172-0.183 mm (0.177 mm) in the anterior segment and 0.0065-0.007822 mm (0.0071 mm) in the posteriors (anchor loss). That accounts for an average of 0.1841 mm space closure per activation or 1.428 mm /month (8 half turn activations). These were similar to the displacement values obtained by McLaughlin *et al*.[21] They reported the displacement produced by a retraction screw was of the magnitude of 0.175 mm. A clinical case study also reported a similar space closure of 1.32 ± 0.22 mm/month or for 8 half turn activation. With active tie backs, an initial displacement of 0.162-0.172 mm (0.1675) was produced in the anterior segment and a negligible amount (unrecordable) of displacement in the posteriors. This is in concordance with the observation reported by Bokas and Woods [36] which showed a displacement of 1.68 mm/month in anteriors and 0.45 mm anchor loss.

Even though the stress levels in the periodontium produced by retraction screw device was almost 2-3 times that of active tie backs, the displacement produced per activation was within the physiological limits, being less than the width of the periodontium (0.20-0.25 mm), which in turn induces bone remodeling and thus tooth movement results.

CONCLUSIONS

Sequential repetitive loading of the PDL using hycon screw is:

- Beneficial in achieving space closure at a much faster rate of 1.428 mm/month (96.14% of anterior segmental retraction) in comparison with 0.165 mm by active tie backs.
- With minimal deleterious effects to the periodontium as the displacement (0.177 mm/

activation) produced is well within biological limits of the periodontium in comparison with the active tie backs.

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