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Comparison of stress distribution in bone and miniscrew and displacement pattern of maxillary anterior teeth by two methods of en-masse retraction: A 3-D finite element analysis

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Abstract

Introduction: To move the teeth in a desired pattern, the appropriate direction of the force must be selected. An inappropriate force delivers unfavourable stresses in the supporting tissues resulting in poor prognosis. It is very difficult to measure stresses accurately in vivo. Finite element analysis provides a definitive solution.

Aim: To compare the stress distribution in bone and miniscrew and displacement pattern of maxillary anterior teeth with two methods of en-masse retraction i.e. NiTi coil spring and elastomeric chain, with miniscrews placed at various heights using finite element analysis.

Materials and Methods: Total of four models were created i.e. two models with retraction by elastomeric chain and two models with retraction by NiTi coil spring with the help of implant placed at 3 mm and 5 mm height from alveolar crest. Results were represented in the form of stress diagrams.

Results and Conclusions: Retraction with elastomeric chain produces lesser amount of von Mises stress on the bone as well as mini-implant as compared to that with NiTi coil spring.

Retraction with elastomeric chain produced more sagittal and vertical displacement of canines as compared to its effect on incisors. The overall displacement of anterior teeth in both vertical as well as in sagittal direction was found to be more with elastomeric chain as compared with NiTi coil spring.

Both the methods for retraction resulted in same amount of palatal root movement irrespective of the force vector.

Keywords: Miniscrew; Stress; En-masse retraction; Finite Element Method

Introduction

Among the three stages of comprehensive fixed orthodontic treatment, the second stage i.e. closure of extraction space is one of the most important aspects as it aims to correct the molar and buccal segment relationships to provide normal occlusion.

In sliding mechanics, two commonly used methods for en-masse retraction are elastomeric chain and nickel titanium (NiTi) closed coil springs. Elastomeric chains have drawbacks like rapid force decay. Faster space closure is achieved with NiTi closed coil springs than the elastomeric chain.(1)

Currently, titanium screws are being considered as a source of absolute orthodontic anchorage. Their advantages are easy placement and removal, immediate loading, placement at different anatomic locations including the alveolar bone between the roots of teeth, and low cost.(2)

An inappropriate external force delivers unfavourable stresses in the supporting tissues resulting in poor prognosis.(3) The movement pattern of teeth depends on the force vector, so the appropriate force vector must be selected for tooth movement in desired direction. Therefore, miniscrew should be placed at a position with minimal stress.(4)

It is very difficult to measure stresses accurately around miniscrews in vivo and to achieve an analytical solution for problems involving complicated geometries like the maxilla and the mandible, which are exposed to different kinds of loads. FEM appears to be suitable for simulating complex mechanical stress situations in the maxillofacial region.(5)

Various FEM studies have been done in the past regarding the optimal loading conditions for implant placement,(6) optimal force magnitude loaded to miniscrews,(7) effect of force directions,(3,8) miniscrew placement angle and structure on the stress distribution at the bone miniscrew interface(5,9) the roles of bone quality, loading conditions, screw effects, and implanted depth on the biomechanics of an orthodontic miniscrew system.(10) Influence of various miniscrew design factors, including thread depth, degree of taper, and taper length on insertion torque, pullout strength, stiffness, and screw displacement before failure have also been studied.(11)

Very little data is available in literature regarding the comparison of the stress distribution on miniscrews and bone and displacement patterns of maxillary anterior teeth during en masse retraction with NiTi coil spring and elastomeric chain. The effect of height of miniscrews placement also remains unexplained, so this study was undertaken to compare two methods of retraction with the help of Finite Element Method.

Aim

To compare the stress distribution in bone and miniscrew and displacement pattern of maxillary anterior teeth with two methods of en-masse retraction i.e. NiTi coil spring and elastomeric chain, with miniscrews placed at various heights using finite element analysis.

Objectives

To simulate orthodontic loading for en-masse retraction by two methods i.e. elastomeric chains and NiTi coil spring.

To evaluate the stress distribution in bone and miniscrew after loading of miniscrew and displacement patterns of maxillary anterior teeth with elastomeric chain and NiTi coil spring for en-masse retraction of maxillary anterior teeth.

To evaluate the effect of heights of miniscrew placement on the stress patterns in bone and miniscrew and displacement patterns of maxillary anterior teeth.

Materials and Methods

Finite Element Method (FEM) has the advantage of being applicable to solids of irregular geometries that contain heterogeneous material properties. The FEM provides the orthodontist with quantitative data that can extend the understanding of physiological reactions that occur within the dentoalveolar complex.[13]

Basic steps involved in carrying out FEM are:[13]

- Pre-processing.
- Construction of the geometric model
- Conversion of the geometric model into a finite element model.
- Assembly/Material Property data representation.
- Defining the boundary conditions.
- Loading Configuration.
- Processing.
- Post-processing.

For this study total of four models were created i.e. two models with retraction by elastomeric chain with the help of implant placed at 3 mm and 5 mm height from alveolar crest and two models with retraction by NiTi coil spring with the help of implant placed at 3 mm and 5 mm height from alveolar crest. To model the irregular geometry of the tooth, tetrahedron shape was selected as the finite element. These elements are connected to each other at the nodes. In this study the total no. of elements used were 294124 and nodes were 66448.

The different structures involved in this study include alveolar bone, periodontal ligament, teeth, nickel titanium coil spring, elastomeric chain, stainless steel arch wire and hook and titanium mini implant. Each structure has a specific material property. Since the elastomeric chain is a polyurethane material, as reported by T. Eliades et al,[16] elastomeric chain was given the properties of polyurethane.[17] These material properties were the average values reported in the literature.

Table 1: Material Properties

Material	Young' s Modulus N/mm2	Poisson's ratio
Tooth[15]	2.0×10^{3}	0.30
PDL[15]	6.8×10^{-2}	0.49
Alveolar Bone[15]	1.4×10^{3}	0.38
Bracket[15]	21.4×10^{3}	0.30
Arch wire/ hook[15]	21.4×10^{3}	0.30
NiTi coil spring[5]	110×10^{3}	0.35
Mini Implant[5]	110×10^{3}	0.35
Elastomeric Chain[16,17]	0.025×10^{3}	0.5

After preparation of four models, constant retraction force of 150 grams were applied in each model bilaterally from miniscrew to power arm of 3 mm length placed between the lateral incisor and canine.[14]

Results

Stresses (MPa) in the miniscrew and the alveolar bone during en-masse retraction and displacement (mm) of the anterior teeth were calculated and presented in form of stress diagrams.

Determination of Von Mises Stress in alveolar bone- (Fig. 2a,b and 3a,b).

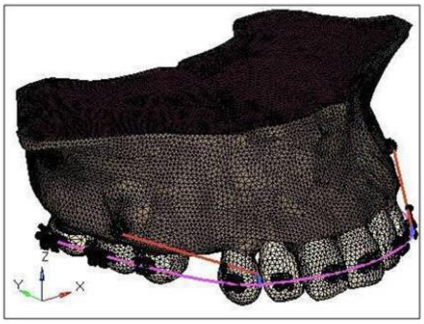


Fig. 1: Final FEM model

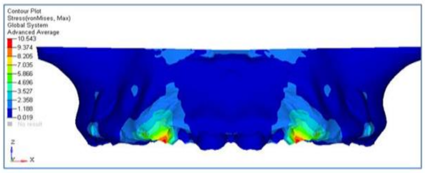


Figure 2a. Bone stresses with Elastomeric chain with miniscrew at 3 mm.

Figure 2b. Bone stresses with NiTi coil spring with miniscrew at 3 mm.

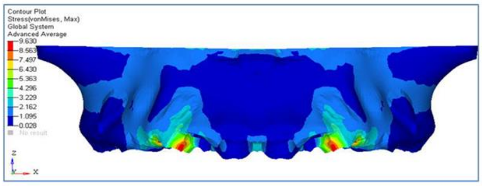


Figure 3a. Bone stresses with Elastomeric chain with miniscrew at 5 mm.

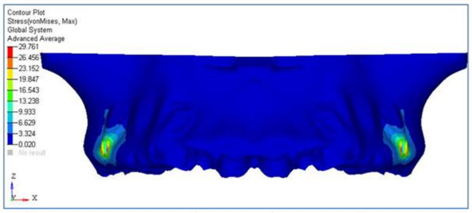
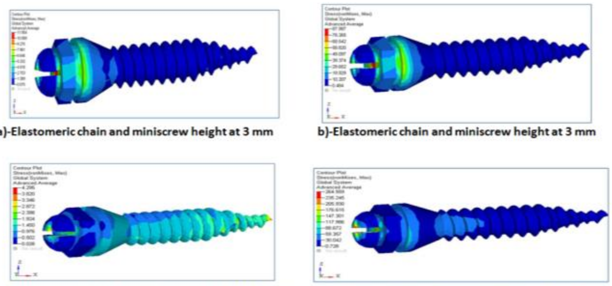


Figure 3b. Bone stresses with NiTi coil spring with miniscrew at 5 mm.

Highest stress value of 29.76 MPa was seen at bone-miniscrew interface when the retraction was done by NiTi coil spring with the miniscrew placed at 5 mm height, followed by stress of 25.889 MPa at bone-miniscrew interface when the retraction was done by NiTi coil spring with the miniscrew placed at 3 mm height. Retraction with elastomeric chain showed significantly lower values of stresses in bone i.e. 10.54 MPa between Lateral Incisor and canine region when miniscrew was placed at 3 mm height and 9.63 MPa between Lateral Incisor and canine region when miniscrew was placed at 5 mm height (Graph 1).

Determination of Von Mises Stress in miniscrew-(Fig. 4a-d)



a)-Elastomeric chain and miniscrew height at 3 mm

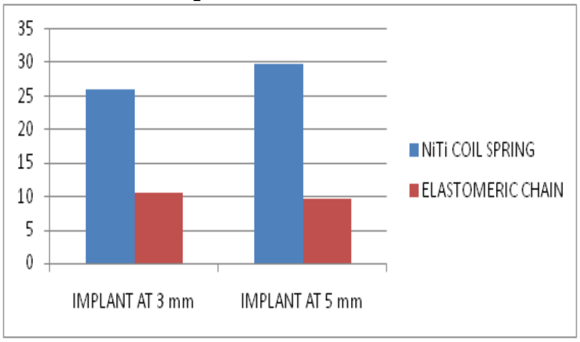
b)-Elastomeric chain and miniscrew height at 3 mm

c)-Elastomeric chain and miniscrew height at 5 mm

d)-Elastomeric chain and miniscrew height at 5 mm

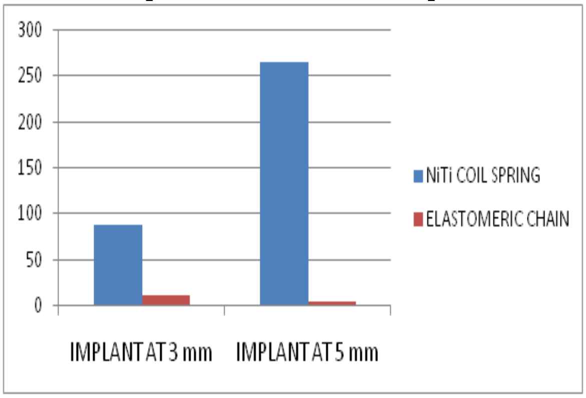
Fig. 4: Stress pattern in miniscrew

Graph 1: Stresses in bone



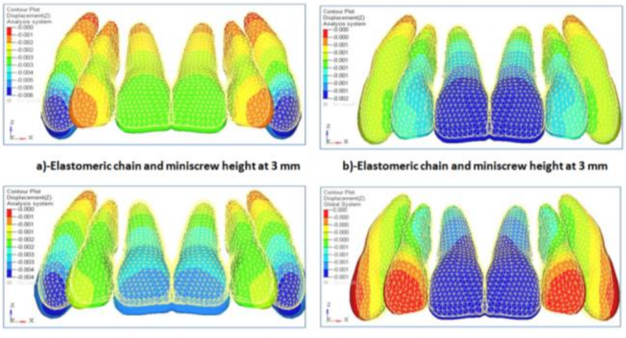
Highest stress value of 264.56 MPa was seen in the miniscrew head when the retraction was carried out with the help of NiTi coil spring with miniscrew placed at 5 mm height, followed by stress of 87.987 MPa in the miniscrew head when the retraction was carried out with the help of NiTi coil spring with miniscrew placed at 3 mm height. Retraction with elastomeric chain showed a significantly lower values of stresses in miniscrew i.e. 11.9 MPa at miniscrew head when miniscrew was placed at 3 mm height and 4.29 MPa at miniscrew tip when miniscrew was placed at 5 mm height.(Graph 2)

Graph 2: Stresses in mini-implant



Displacement patterns of upper anterior teeth-

a. **In Vertical Direction – (Fig. 5):** Greater amount of extrusion of canine (0.006 mm and 0.004 mm) was noted during retraction with elastomeric chain followed by extrusion of incisors (0.004 mm and 0.003 mm) when the mini-implant was placed at 3 mm and 5 mm heights respectively.



a)-Elastomeric chain and miniscrew height at 3 mm

b)-Elastomeric chain and miniscrew height at 3 mm

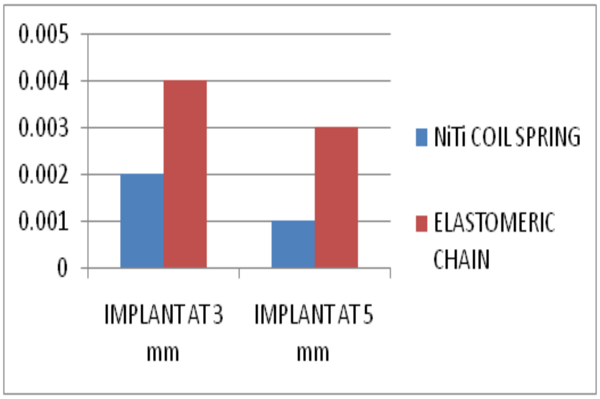
c)-Elastomeric chain and miniscrew height at 5 mm

d)-Elastomeric chain and miniscrew height at 5 mm

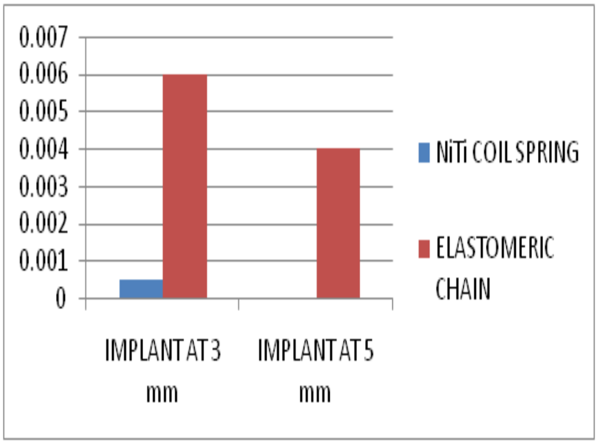
Figure 5. Displacement pattern in vertical direction

On the contrary, extrusion was seen only in central incisors with the use of NiTi coil spring (0.002 mm and 0.001 mm with mini-implant placed at 3 mm and 5 mm height respectively), with minimal or no extrusion of any other tooth. (Graph 3a and b)

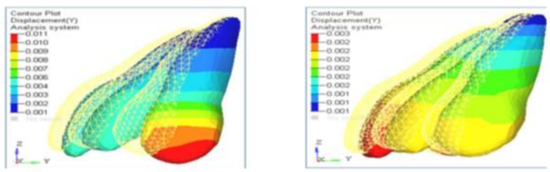
Graph 3a: Vertical displacement patterns of upper central incisors



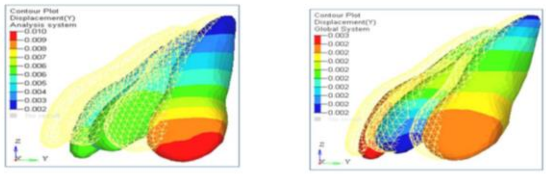
Graph 3b: Vertical displacement patterns of upper canines



b. **In Sagittal Direction (Fig. 6):** More palatal movement of canine (0.011 mm and 0.010 mm) was observed during retraction with elastomeric chain when the mini-implant was at 3 mm and 5 mm heights respectively. The palatal movement of incisors were to a lesser degree of 0.006 mm, similar for both the mini-implant placement heights.



a)-Elastomeric chain and miniscrew height at 3 mm b)-Elastomeric chain and miniscrew height at 3 mm

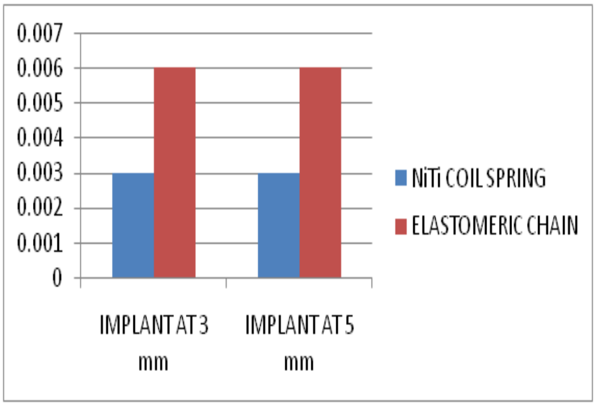


c)-Elastomeric chain and miniscrew height at 5 mm d)-Elastomeric chain and miniscrew height at 5 mm

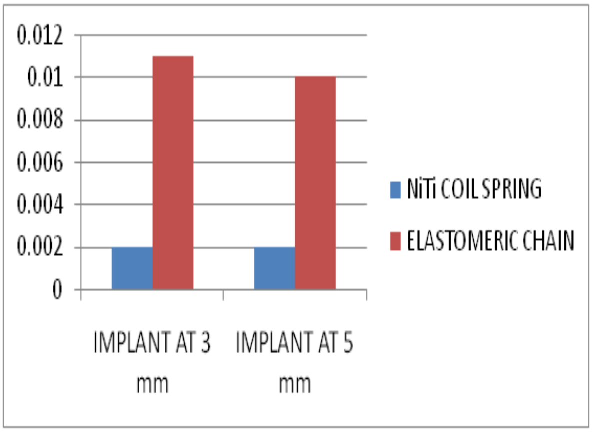
Figure 6. Displacement pattern in sagittal direction

On the other hand, when the retraction was done by NiTi coil spring, the maximum palatal movement was noted in central incisors (0.003 mm) which was similar for both mini-implant placement heights. The palatal movement of lateral incisors and canines were to a lesser degree of 0.002 mm, similar for both the mini-implant placement heights. (Graph 4 a and b)

Graph 4a: Sagittal displacement patterns of upper central incisors

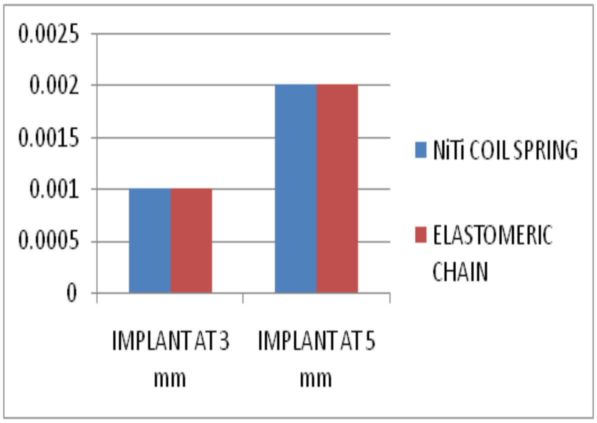


Graph 4b: Sagittal displacement patterns of upper canines



c. **The root movement:** At 5 mm miniscrew height, 0.002 mm of palatal root movement of anterior teeth was seen with both the retraction methods which was more than (0.001 mm) that with miniscrew position at 3 mm height. (Graph 5)

Graph 5: Palatal root movement ot upper anterior teeth



Discussion

FEM has certain limitations. This technique is based on several assumptions which were made in the development of the model for this study. All the models were assumed to be homogenous and isotropic and to have linear elasticity.

The material properties and the geometry of the model change from one person to another. The stress distribution patterns simulated also might be different, depending on the materials and properties given to each layer of the model used in the experiments. These are inherent limitations of this technique.[5]

The clinical success of a miniscrew is mainly determined by the manner in which the mechanical stresses are transferred from the miniscrew to surrounding bone without generating forces of a magnitude that would jeopardize the longevity of the miniscrew.[9]

This study is the first FEM study to attempt direct comparison of the stress patterns, in bone and miniscrew and displacement patterns of maxillary anterior teeth associated during en-masse retraction, with elastomeric chains and NiTi coil springs along two different force vectors.

The power arm for en-masse retraction was placed in between lateral incisor and canine as suggested by Teasoo Kim et al.[19] According to them the application of a retraction force at this location indicates stable movement of the anterior teeth.

As described by Kee-Joon Lee et al,[20] the "line of force" is determined by simply connecting the line between the miniscrew head and the hooks on the wire, and it is obvious that varying miniscrew positions would create different force vectors. Similarly in this study the miniscrews were placed at two different heights i.e. 3 mm and 5 mm from the alveolar crest.

Von Mises stress in bone: Bone tissue is known to remodel its structure in response to mechanical stress.[23] According to Meijer et al low stress levels around a miniscrew may result in poor connection with bone or bone atrophy.[24] On the other hand, according to Lavernia et al abnormally high stress concentrations in the supporting tissues can result in pressure necrosis and subsequently in miniscrew failure.[25]

The results of this study showed that the maximum amount of Von Mises stress in bone with the use of NiTi coil spring was at the bone and miniscrew interface in the cortical bone area with minimal stress on deep cancellous bone. These findings are similar to the findings of Liu et al,[10] who suggested that cortex thickness determines the overall load transfer from miniscrew to bone, and the density of cancellous bone plays only a minimal role in resisting this force. He suggested 2 reasons for this. First, cortical bone has a higher Young's modulus, therefore resists more deformation and sustains higher loads than does cancellous bone. Second, the bending mode, as identified in the mini screw stress, has more effect at the base support region, as justified by the concentrated high base stress in the entrance region at the cortex than the rest of the embedded region, a straighter and less bent region.

The results from stress diagrams suggest that the stresses in bone are more at the bone miniscrew interface when retraction is done with NiTi coil spring than that of elastomeric chain. On the other hand stresses in the alveolar bone of anterior teeth are mainly seen with the retraction by means of elastomeric chain. In case of retraction with elastomeric chain stresses in bone decreased when the miniscrew height was increased from 3 mm to 5 mm while vice versa is true for NiTi coil spring.

All the stress values in the bone are well below the yield stress of the bone (200 MPa)[9] indicating that the bone has sufficient strength to resist retraction forces by both the methods with variable heights of miniscrew placement in clinically acceptable range.

Von Mises stresses in miniscrew: The stresses in miniscrew showed variable pattern i.e. stresses associated with NiTi coil spring were significantly greater than that of elastic chain. Stresses in miniscrew showed similar pattern i.e. in case of retraction with elastomeric chain stresses in miniscrew decreased when the miniscrew height is increased from 3 mm to 5 mm. on the other hand when retraction was done with NiTi coil spring, stresses in miniscrew increased when the miniscrew height was increased from 3 mm to 5 mm.

As stated by Singh et al,[12] the finite element model neglects the stress produced by the insertion of the screw and considers only the stresses produced by horizontal and torsional loads. In spite of these limitations, the finite element predictions in our investigation are in good agreement with the results of Gallas et al,[21] and Szuhanek et al,[22] who reported that, when force was applied perpendicularly to the long axis of the miniscrew, the maximum stresses were located around the head and neck of the miniscrew at the bone-miniscrew interface. The increased stress values obtained at the head region of the Miniscrew might be explained by the reduced bulk (quantity) of the material in this region.[12] In short, the stress values in bone as well as miniscrew were more when retraction was carried out with NiTi coil spring as compared to that with elastomeric chain.

Similar to the bone stresses, the stress values in the miniscrew were also below the yield stress of titanium (692 MPa)[9] indicating that the miniscrew has sufficient strength to resist retraction forces by both the methods with variable heights of miniscrew placement in clinically acceptable range.

When the miniscrew is placed at a height of 5 mm and retraction is done with elastomeric chain, it produces least amount of stresses in the bone as well as the miniscrew. On the other hand when the miniscrew placed at a height of 5 mm and retraction is done with NiTi coil spring, it produces maximum amount of stresses in the bone as well as the miniscrew.

These variations in stress patterns in the bone and the miniscrew could be the result of different material properties of elastomeric chain and NiTi coil spring which were used for retraction.

Vertical displacement patterns of anterior teeth: More amount of extrusion was seen in canines followed by central incisors with the use of elastomeric chain. On the contrary, extrusion was seen only in central incisors with the use of NiTi coil spring, with minimal or no extrusion of any other tooth.

This extrusion can be explained by the force vector that was below the center of resistance of maxillary anterior teeth. Retraction force with miniscrew anchorage produced rotation of entire arch around center of rotation near premolar root, which may result in intrusion of maxillary posterior teeth and extrusion of anterior teeth[26]. As the mini-implant height was increased the amount of extrusion was decreased in both the retraction mechanisms. This can be explained by the direction of force vector moving closer to the center of resistance of maxillary anterior segment. According to Tominga et al[6] in sliding mechanics, the height of the retraction force affects the type of anterior tooth movement, so that the force system for a desired type of movement can be designed by changing the direction of force vector.

Min –Ho Jung et al[26] stated that the use of miniscrews for anchorage reinforcement produces the mechanics different from conventional mechanics. Because the force used during retraction is not reciprocal, either the entire arch or the anterior segment will rotate around the center of rotation.

Sagittal displacement patterns of anterior teeth: According to Kee-Joon Lee et al[20] varying miniscrew positions would create different force vectors and change the line of force. In this study when the retraction was done by elastomeric chain, the maximum palatal movement was noted in canines followed by incisors. On the other hand, when the retraction was done by NiTi coil spring, the maximum palatal movement was noted in central incisors followed by lateral incisors and canines.

Some amount of palatal root movement was also observed during en-masse retraction of anterior teeth. When the mini-implant was placed at 5 mm height, 0.002 mm of palatal root movement of anterior teeth was seen with both the retraction methods. A lesser degree of palatal root movement of anterior teeth (0.001 mm) was seen with both the retraction methods when the mini-implant was placed at 3 mm height.

These findings suggest the controlled palatal tipping movement of maxillary anterior teeth during the application of retraction forces from mini-implant. These results are similar to the study by Madhur Upadhyay et al[2] who observed that the retraction with implants was primarily achieved by controlled tipping and partly by translation because the forces applied were closer to the center of resistance of the maxillary anterior teeth.

All the findings from stress analysis in present study suggest that the retraction with elastomeric chain produces lesser amount of von Mises stress on the bone as well as mini-implant as compared to that with NiTi coil spring. Retraction with elastomeric chain produced more effect on canines in terms of sagittal and vertical displacement as compared to its effect on incisors. And the overall displacement of anterior teeth in both vertical as well as in sagittal direction was found to be more with elastomeric chain as compared with NiTi coil spring. Both the methods for retraction resulted in same amount of palatal root movement depending on the force vector, i.e. as the height of mini-implant increased the root movement was also increased.

As suggested by Yukio Kozima et al,[4] the simulations in FEM study are based on mechanical laws, and their results are valid only within the boundaries of these assumptions. This method may not be sufficient for predicting orthodontic tooth movements in clinical scenario. During orthodontic treatment, various forces act continuously on the maxillary teeth from the mandibular teeth, the tongue, and the cheek. The amount and direction of these forces are difficult to determine, and their effect on orthodontic tooth movement is not clear.

Therefore, correlating FEM results with preclinical and long-term clinical studies may help to validate research models.[18]

Conclusions

The following conclusions were drawn after performing the study and by careful interpretation of results:

NiTi coil spring showed significantly higher level of Von Mises stresses in bone as well as miniscrew when compared with elastomeric chain applying similar amount of retraction force.

Height of miniscrew placement affected the stress pattern in both the retraction methods but in opposite manner, i.e. as the height of miniscrew increased from 3 mm to 5 mm, the stress values increased in NiTi coil spring retraction models, while the stress values decreased in elastomeric chain retraction models.

Retraction with NiTi coil spring showed greater amount of extrusion and palatal movement of central incisors while extrusion and palatal movement of canines were present with retraction by elastomeric chain. And the overall displacement of anterior teeth in both vertical as well as in sagittal direction was found to be more with elastomeric chain as compared with NiTi coil spring.

Increasing the height of miniscrew placement encouraged the translatory movement of anterior teeth because as the height of mini-implant increased the root movement was also increased.

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