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Comparative evaluation of effectiveness of three versus four mini-implants for simultaneous intrusion and retraction of maxillary anterior teeth: A 3D FEM study

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Abstract

OBJECTIVE: To evaluate and compare the displacement pattern of maxillary anterior teeth in the sagittal and vertical planes and evaluate the stress distribution in pdl, bone, teeth of the maxillary anterior region, and around the mini-implants during simultaneous en-masse retraction and intrusion using two, three, and four mini-implants combinations.

METHODS: A three-dimensional FEM model of maxillary teeth and periodontal ligament housed in the alveolar bone with extracted first premolarswasgenerated. The models were broadly divided into three groups according to the number of mini-implants. Mini-implants were placed bilaterally between the second premolar and molar in group I, and along with bilateral implants, an additional mid-implant was placed between the central incisors as in group II, whereas in group III, anterior mini-implants were placed in between lateral incisors and canine bilaterally.

RESULTS: The two mini-implant model showed the maximum amount of retraction in the sagittal plane followed by three and four mini-implant models. In the vertical plane, all six anterior teeth showed intrusion only in the four mini-implant model.The stress in cortical bone, cancellous bone, PDL, around the mini-implants, and in lateral incisor was maximum in the three mini-implant model, followed by four mini-implants with the least stress in the two mini-implant model.

CONCLUSION: The four mini-implant model is better than the three and two mini-implants model as there is a more even distribution of force in the four mini-implants model as compared to the three mini-implants model.

Keywords:

En-masse retraction, finite element method, intrusion, mini-implants

Introduction

Malocclusion can occur in three planes of space, that is, sagittal, transverse, and vertical planes. Many ethnic groups all around the world have a high prevalence of dental protrusion with a deep overbite.[1] One of the ways of treatment modalities is by extracting the first premolars and retracting the anterior segment. However, the correction of a deep overbite in patients with flared incisors is a critical biomechanical issue during orthodontic therapy because uprighting of incisors often lengthens the crowns vertically, increasing the overbite.[1]Thus, in most extraction cases, the retraction of the flared maxillary anterior teeth has to be followed by intrusion, which

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further increases the treatment time. Thus, there is a need for simultaneous retraction and intrusion of the anterior segment.[2]

Conventional treatment modalities for simultaneous intrusion and retraction of the anterior segment such as the retraction and intrusion utility arch, three-piece intrusion arch, and K-SIR arch, result in undesirable side effects such as posterior tooth extrusion. Extrusion of posterior teeth will result in increased lower facial height, steepens the occlusal plane, and causes downward and backward rotations of the mandible, resulting in a worsening of the Class II skeletal relationship.[3]

With the introduction of mini-implants, anchorage can be achieved with minimum patient compliance in orthodontic treatment. Mini-implants can provide good anchorage for simultaneous retraction and intrusion and can be placed in the most desired locations.[1]The intrusion of upper and lower incisors, reducing overbite, can be easily achieved by placing mini-implants in anterior interradicular areas and applying the appropriate orthodontic mechanics. One or two mini-implants may be placed between central incisors, central and lateral incisors, or lateral incisors and canines for intrusion of maxillary anterior teeth; however, a good outcome with minimal incisor protrusion depends upon the correct location of mini-implants.[4]

Finite element analysis (FEA) is a method that is utilized to evaluate biomechanical parameters after orthodontic forces have been applied. This method can simplify the physiologic responses of the dentoalveolar complex to orthodontic forces by exhibiting quantitative data and is recently preferred by researchers in the field. The primary benefit of using FEA is that numerous alternative designs may be tested for validity, safety, and integrity using a computer before the first prototype is created for clinical use.

With the passage of time, manyFEM studies have been conducted that evaluated the stress and displacement pattern in two and three mini-implant combinations by placing two mini-implants in the posterior region for retraction and one anterior mini-implant for intrusion.[5] However, there are limited studies available that have evaluated the stress and displacement pattern in the two, three, and four mini-implants models.

So, this FEM study was conducted to evaluate the stress distribution in PDL, bone, and teeth of the maxillary anterior region and around the mini-implants and also to compare the displacement pattern of maxillary anterior teeth in the sagittal and vertical plane in two, three, and four mini-implants models after the application of simultaneous retraction and intrusion force in the anterior segment.

Materials and Methods

Steps involved in the finite element model preparation

1. **Construction of the geometric model of the maxillary dentition with its periodontal structures** (**PDL, alveolar bone**)**-**This step involved the creation of a geometric representation of maxillary teeth, alveolar bone, wires, and brackets. The CBCT scan of the maxilla of an adult patient with a full permanent dentition was used to create geometric models of the maxillary central and lateral incisors, canines, second premolars, and first molars. The images were saved as DICOM files and were later exported to a three-dimensional (3D) image-processing software. A geometric model based solely on surface data was created using Fusion 360 software. Ethical committee approval obtained and date of approval on 28-06-2021.

2. Conversion of the geometric models to a finite element model

The geometric models were transformed into finite element models using the HYPERMESH (version 18) software. The finite element model is representative of geometry in terms of the finite number of elements and nodes. This process is called ”discretization.”

3. Incorporation of material properties of tooth structure and periodontium

The material properties of teeth, PDL, and alveolar bone used were the average values reported in the literature. It was assumed that all materials used in the finite element model investigation were homogenous, isotropic, and linearly elastic. To create models that as closely resemble reality as possible, Young’s modulus and Poisson’s ratio were utilized [Table 1], and the values for bone density (anterior maxilla-D2 = 850–1250 HU and posterior maxilla-D3 = 350–850 HU) were used in accordance with the study conducted by Chugh *et al*. (2013).[6]

4. Defining boundary condition

After the construction of the finite element model, the boundary condition of these models needs to be established such that all movements of the model are restrained. Such restraint is required to prevent the model from any type of body motion while the load is acting.

5. Loading configuration- In this step, loads of the appropriate amount were defined on a discretized model in ANSYS.

6. Translation of results and interpretation

A FEM consisting of nodes and elements [Table 2] of the teeth, periodontium, brackets, archwire, retraction hooks, mini-implants, and NiTi-closed coil springs wasthen imported into the ANSYS [19.2 version] software for analyzing the displacement and stress distribution. This step involved creating pictorial and/or tabular representations of stresses.

In this study, three finite element models of maxillary teeth and periodontal ligament housed in the alveolar bone with extracted first premolars were generated with an appropriate number of elements and nodes.

The models were broadly divided into three groups-

Group I-Two mini-implants were placed between the roots of the second premolar and the first molar. In this model, retraction force was applied bilaterally to retract the anterior teeth [Figure 1a].

Group II-Along with two posterior bilateral mini-implants, an additional mid mini-implant was placed in between the roots of two central incisors. In this model, a retraction force was applied from posterior bilateral mini-implants and an intrusive force was applied from mid-mini-implant [Figure 1b].

Table 1: Material parameters to be used in finite element model

Material	Young's modulus (N/mm^2)	Poisson's ratio
Enamel	8.41×10^4	0.3
Dentin	1.83×10^4	0.30
Pulp	0.5–99.9	0.45
Periodontal ligament	6.90×10^{-1}	0.45
Bone	1.37×10^4	0.30
Cortical bone	3.45×10^5	0.45/0.26
Cancellous bone	1.37×10^4	0.38
Stainless steel wire and brackets	210×10^3	0.3
Titanium implants	110×10^3	0.3
NiTi coil spring	110×10^3	0.35
Elastomeric chain	0.025×10^3	0.5

Group III-In this, along with two posterior bilateral mini-implants, two additional anterior mini-implants were placed between the roots of the lateral incisor and canine bilaterally. In this model, retraction force was applied from posterior bilateral mini-implants and intrusive force from both anterior mini-implants [Figure 1c].

- Brackets with 0.022 slot with MBT prescription were placed on the teeth with 0.019 × 0.025 SS wire placed in the brackets.
- In all three groups, posterior bilateral mini-implants (1.3mm × 8 mm) were placed at a height of 10mm from the archwire, and an anterior retraction hook was placed between the canine and lateral brackets at a height of 9mm from the archwire. The anterior mini-implants (1.3 × 8mm) were placed at a height of 12mm from the archwire.
- In all three groups, bilateral posterior mini-implants were angulated to 30 degrees to the long axis of the occlusal plane and in the second and third groups, anterior mini-implants were placed perpendicular to the occlusal plane.
- In all three groups, 150 g retraction force was applied bilaterally from mini-implants (direct–anchorage) located between the second premolar and first molar onto the retraction hooks attached between the lateral incisor and canine using a NiTi-closed coil spring.
- In the second group, along with the retraction force, the intrusive force of 60g was applied from the anterior mid mini-implant through the e-chain, whereasin the third group, the intrusive force of 30g per side was applied from two anterior mini-implants through the e-chain along with retraction force.

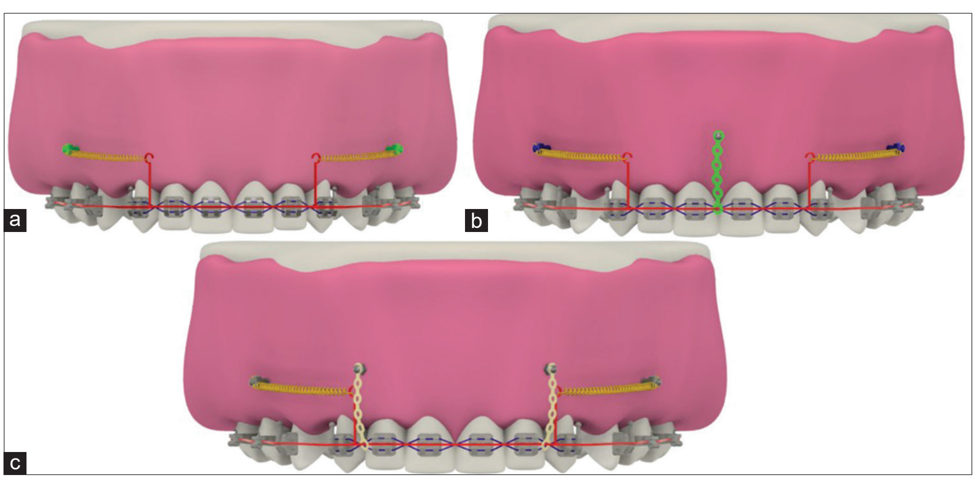

Figure 1: FEM maxillary model. (a) Two mini-implants, (b) three mini-implants, and (c) four mini-implants model

In all three models, an anterior segment was consolidated.

Results

The displacement in the anteroposterior direction (Z axis) was the maximum in the two mini-implant model(-6.4659×10^{-4}), followed by the three mini-implant model[-6.5435×10^{-5}) with the minimum displacement in four mini-implants model(-6.0345×10^{-5})[Table 3].

The displacement in the vertical direction (Y axis) showed that in the two mini-implants model, all anterior six teeth exhibited extrusion. Central and lateral incisors exhibited intrusion in the three mini-implants model, whereas the canine showed extrusion. In contrast, in the four mini-implants model, all the teeth, central and lateral incisors, and canine showed intrusion [Table 4].

The von Mises stress in the cortical bone was higher in the three mini-implants (1.1241 MPa) model, followed by four mini-implants (0.83674MPa) with the least stress in two mini-implants model (0.48441 MPa)[Table 5].

The highest von Mises stress in the cancellous bone was observed in the three mini-implants (0.36544 MPa) model, followed by four mini-implants (0.20853 MPa) with the least stress in two mini-implants model (0.11234 MPa)[Table 6].

The maximum von misses stress in the periodontal ligament were found in three mini-implants (0.15288MPa) model, followed by four mini-implants (0.13781MPa) with the least stress in two mini-implants model (0.11627 MPa). However, the stress on the PDL of the lateral incisor showed the maximum stress in all three models[Table 7].

The von Mises stress in the posterior mini-implants was almost the same in all three models. However, one anterior mini-implant in the three mini-implants model showed a maximum stress of 6.0763 MPa and it was observed up to the second thread of mini-implant as compared to the anterior mini-implants in the four mini-implants group, which had a stress value of 4.3543 MPa observed at the head and neck regions of mini-implant[Table 8].

Among all the six anterior teeth, the maximum von Mises stress was observed in the lateral incisor in all three models. The lateral incisor of three mini-implants model (0.59960 MPa) showed the maximum stress, followed by four mini-implants (0.59653 MPa) with the least stress in two mini-implants model (0.58036 MPa) [Table 9].

Table 2: Number of elements and nodes in FEM models

	Number of elements	Number of nodes
Group-I (Two mini-implants model)	1,572,501	378,898
Group-II (Three mini-implants model)	2,079,689	476,581
Group-III (Four mini-implants model)	873,674	225,752

Discussion

Displacement in the sagittal plane

The maximum amount of retraction was observed in the two mini-implant model as compared to three mini-implants and four mini-implant models [Figure 2]. Further, when we compared the amount of retraction in the three and four mini-implants model, the three mini-implants model showed more retraction as compared to the four mini-implants. As the intrusive component of force was added in the three and four mini-implants models, retraction of the anterior segment decreased because the tooth was facing two different types of forces in two different directions simultaneously. This was also supported by the study by Namburi *et al*.,[5] which also found a decreased amount of retraction in the anterior segment in the three mini-implants model as compared to the two mini-implants model. Bariar*et al*.,[7] also supported the same that the amount of retraction observed in the four mini-implant model was less as compared to the three mini-implant models.

In each of the three models, the crown moved more as compared to the apex of the teeth. The reason might be due to resistance offered by the bone near the apex being greater than the crown. Also, the canine moved more as compared to centrals and laterals in the sagittal plane. The reason might be the retraction force was more toward the canine. It appeared that in the two mini-implant model, the canines exhibited more palatal tipping compared to the three and four mini-implant models. This might be due to the lack of a vertical component in the two mini-implant models, resulting in less control over the movement of the canines. Additionally, the archwire

Table 3: Comparison of displacement of six anterior teeth in the anteroposterior direction [Z axis]

	CANINE		LATERAL INCISOR		CENTRAL INCISOR	
	CROWN	APEX	CROWN	APEX	CROWN	APEX
Two mini-implants	-6.4659×10^{-4}	-9.5946×10^{-5}	-4.2578×10^{-4}	-3.6095×10^{-4}	-3.5036×10^{-4}	-2.8475×10^{-4}
Three mini-implants	-6.5435×10^{-5}	-5.9389×10^{-5}	-3.7084×10^{-5}	-3.1185×10^{-5}	-2.5692×10^{-5}	-2.0172×10^{-5}
Four mini-implants	-6.0345×10^{-5}	-5.5742×10^{-5}	-2.5443×10^{-5}	-2.5111×10^{-5}	-2.1611×10^{-5}	-1.7105×10^{-5}

Inference: + sign is labial movement; - sign is palatal movement torsion in the two mini-implant models may have contributed to insufficient torque transmission to the maxillary canines, further contributing to palatal crown tipping. Zhang *et al*.[8]suggested that this lack of torque expression may have been responsible for the observed differences in canine movement between the two models.

Displacement in the vertical plane

In two mini-implants, all six anterior teeth showed extrusion as expected. In contrast, in the three mini-implants group, central and lateral incisors showed intrusion [Figure 3]. Placing a mini-implant between two central incisors in the midline helps to apply additional

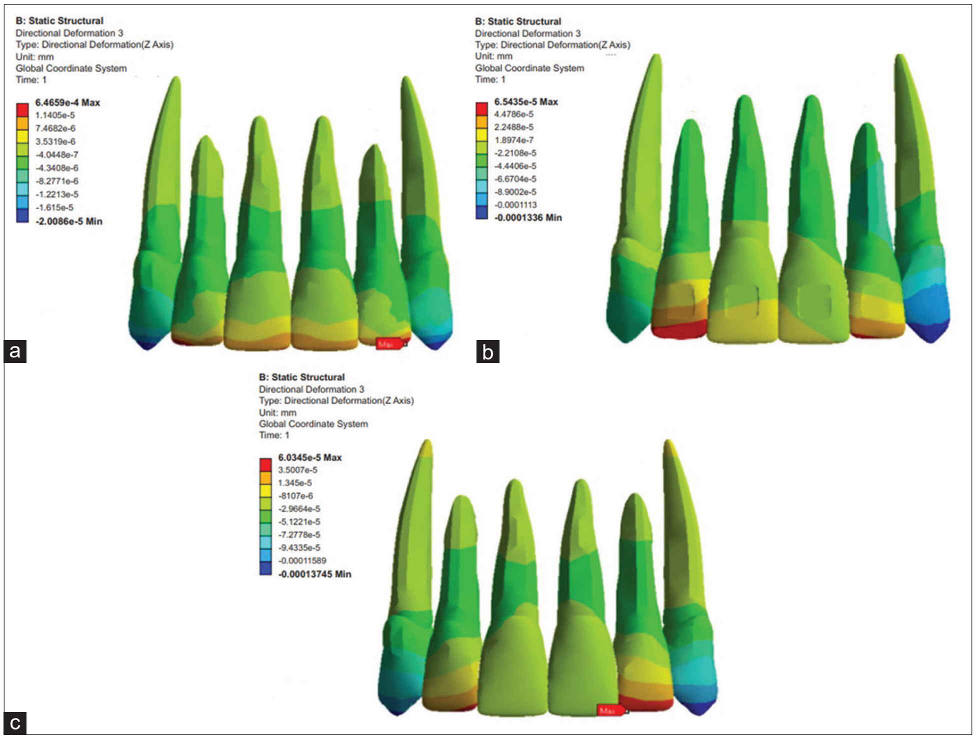

Figure 2: Displacement pattern in the sagittal direction in (a) two mini-implants, (b) three mini-implants, and (c) four mini-implants model

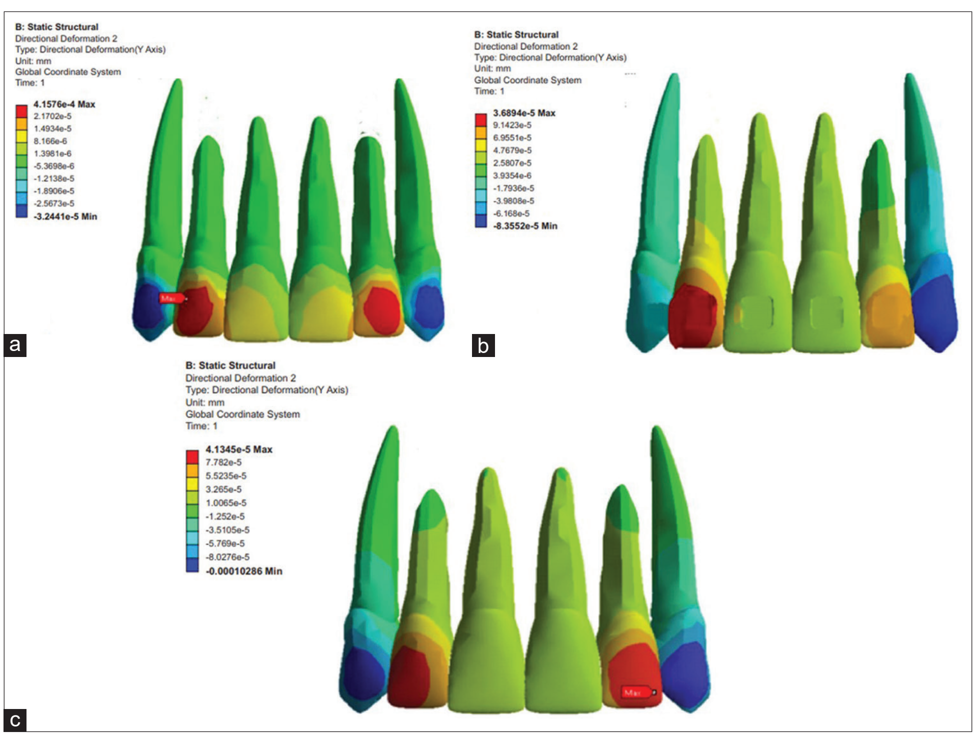

Figure 3: Displacement pattern in vertical direction in (a) two mini-implants, (b) three mini-implants, and (c) four mini-implants model

vertical components of intrusion forces and a direct effect on the central incisors was expected. However, canine still showed extrusion although the amount of extrusion seen in canine in three mini-implants was less as compared to the two mini-implants group. This was because the force applied from the central mini-implant was far from the canine and thus had less effect on the movement of the canine in the vertical plane. This was in accordance with the study performedby Bohara *et al*.[1] and Namburi *et al*.,[5]who also found similar results. In the four mini-implants group, canine also intruded along with central and lateral incisors, this was because of a change in position and number of TADs. This means that for even distribution of force, placing the TADs in between lateral incisors and canine is better than placing TADs in between central incisors. This was also observed in the study performed by Bariar *et al*.[7] intrusive components were observed on the archwire mainly in the anterior region and it gradually decreased away from the {point of force application in the three mini-implants group and four mini-implants group. Also, the center of resistance of the six anterior teeth was estimated to be halfway between the lateral incisors and canines.[9]True intrusion without axial inclination change can only be obtained by directing the intrusive force through the center of resistance of the anterior teeth, which better can be achieved with the four mini-implants model.[9]

Table 4: Comparison of displacement of six anterior teeth in the vertical direction [Y axis]

	CROWN		
	CANINE	LATERAL INCISOR	CENTRAL INCISOR
Two mini-implants	-4.1576×10^{-4}	-2.0554×10^{-5}	-2.0859×10^{-5}
Three mini-implants	-3.6894×10^{-5}	$+3.3651\times10^{-5}$	$+2.2336\times10^{-5}$
Four mini-implants	$+1.2417\times10^{-5}$	$+4.1345\times10^{-5}$	$+1.7223\times10^{-5}$

Inference: + sign is intrusion movement; - sign is extrusion movement

Table 5: Comparison of von Mises stress in cortical bone

Two mini-implants	Three mini-implants	Four mini-implants
0.48441 MPa	1.1241 MPa	0.83674MPa

Table 6: Comparison of von Mises stress in cancellous bone

Two mini-implants	Three mini-implants	Four mini-implants
0.11234 MPa	0.36544 MPa	0.20853 MPa

Table 7: Comparison of von Mises stress in periodontal ligament

Two mini-implants	Three mini-implants	Four mini-implants
0.11627 MPa-Lateral incisor	0. 15288MPa-Lateral incisor	0.13781MPa-Lateral incisor

Stress in cortical and cancellous bones

Stress values in the cortical bone were more than the cancellous bone in all three models. Our result was in accordance with the various studies conducted by Kalia *et al*.,[10]Sivamurthy*et al*.,[11]and Namburi *et al*.[5]This observation could be explained by the fact that the cortical bone has a higher Young's modulus than the cancellous bone, allowing it to resist more deformation and withstand higher stresses.

Stress in cortical bone in the two mini-implants model was less as compared to the three and four mini-implants model and this same pattern of stress distribution was observed in the cancellous bone as well [Figures 4 and 5].The maximum amount of stress in the cortical bone was observed in the three mini-implants group as compared to the two and four mini-implants groups. Four mini-implants group showed stress, which was less than three mini-implants but more than two mini-implants group. This was in contrast with the study performed by Thakkar *et al*.[12]because the line of force of application was different in both studies. In the FEM study performed by Thakkar *et al*.,[12] the line of force was oblique in the single mini-implant group for intrusion, which created more shear stress as compared to bilateral mini-implants for intrusion, which had a line of force in the axial direction which created more of tensile stress. However, in our study, both in the three and four mini-implants group, the anterior TADs had a line of force in the axial direction, thus creating tensile forces.

In addition to this, there is a difference in the bone density at the buccal cortical plate in basal bone in the incisor region of the maxilla as compared to the canine region,[13]which might also beanother reason for more stress in three mini-implants as compared to four mini-implants group.

Stress in Periodontal Ligament

The present study showed the highest stresses on PDL of lateral incisors in all three models, and this may be due to the fact that lateral incisors have shorter roots than other teeth.[14]According to Viecilli and Burstone,[15] larger teeth

Table 8: Comparison of von Mises stress in mini-implants

	Right posterior mini-implant	Left posterior mini-implant	Anterior mini-implant
Two mini-implants	1.1518 Mpa	1.1991 Mpa	_
Three mini-implants	1.14538 MPa	1.15538 MPa	6.0763 MPa
Four mini-implants	1.1214 MPa	1.1221 MPa	Right anterior implant- 4.2801 MPa Left anterior implant -4.3543 MPa

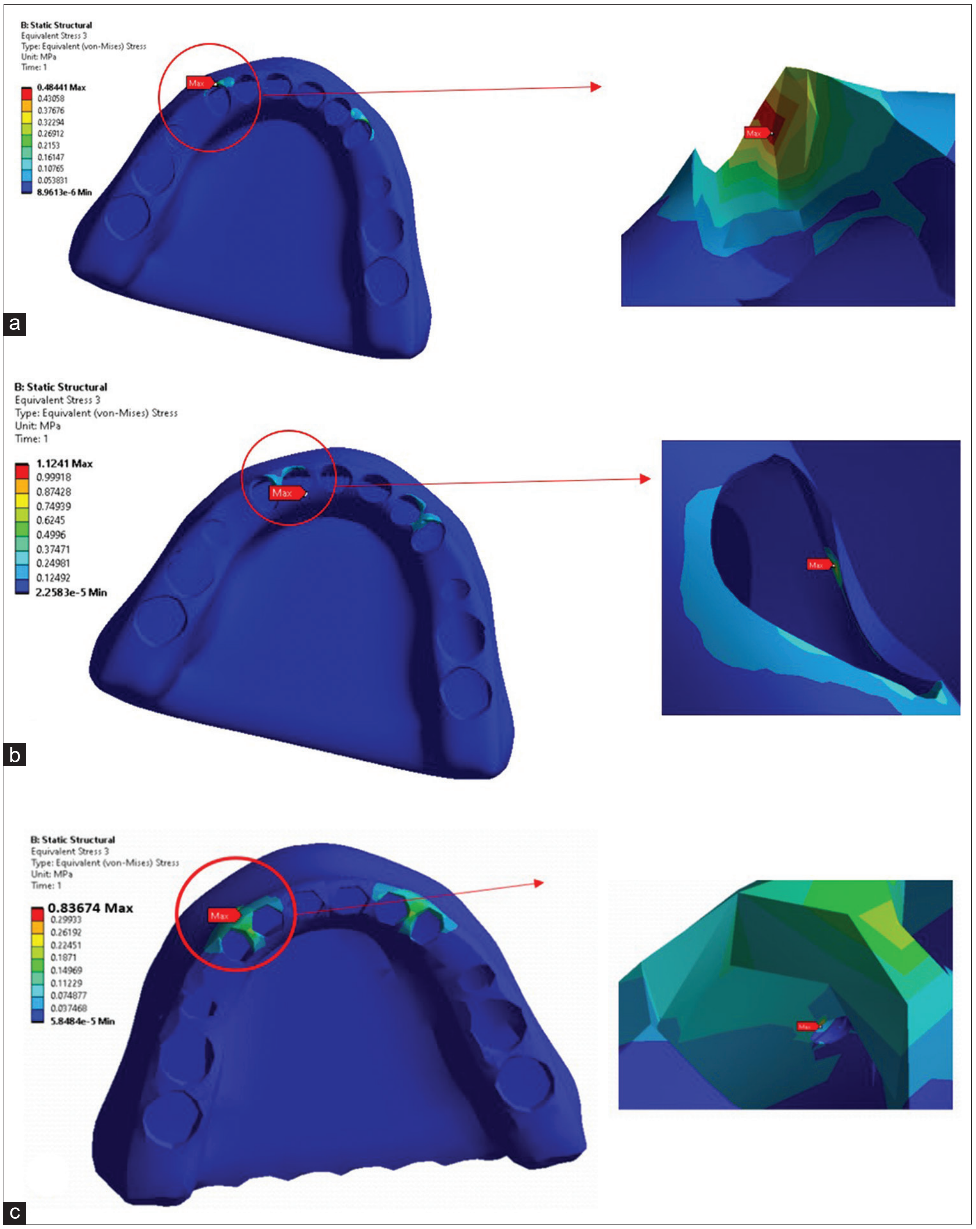

Figure 4: Maximum von Mises stress in cortical bone in (a) two mini-implants (b) three mini-implants and (c) four mini-implant model

Table 9: Comparison of von Mises stress in maxillary six anterior teeth

	Canine	Lateral incisor	Central incisor
Two mini-implants	0.13195 MPa	0.58036 MPa	0.14129 MPa
Three mini-implants	0.13801 MPa	0.59960 MPa	0.15143 MPa
Four mini-implants	0.14406 MPa	0.59653 MPa	0.14936 MPa

have greater PDL and root support than smaller teeth, so when the same load is applied, the stress magnitudes in the PDL for larger teeth are smaller and larger for smaller teeth. The maximum amount of stress in PDL was observed in the three mini-implant model as compared to the four mini-implant model with the least amount observed in the two mini-implant model [Figure 6]. This was because there was a more evenly distributedof force in the four mini-implant model as compared to the three mini-implant model.

Stress in mini-implants

Two mini-implants in the posterior region in all three models had similar stress and which was mostly at the head of the mini-implant [Figure 7]. However, the anterior mini-implant in the three mini-implants model showed the maximum stress as compared to the four mini-implant group [Figure 8]. This was in accordance with the study conducted by Naqeed *et al*.,[9] who had also found more stress in a single mini-implant in the anterior region and it could lead to mini-implant failure, which suggested that when two mini-implants in the anterior region are placed, it decreased stresses in mini-implants.

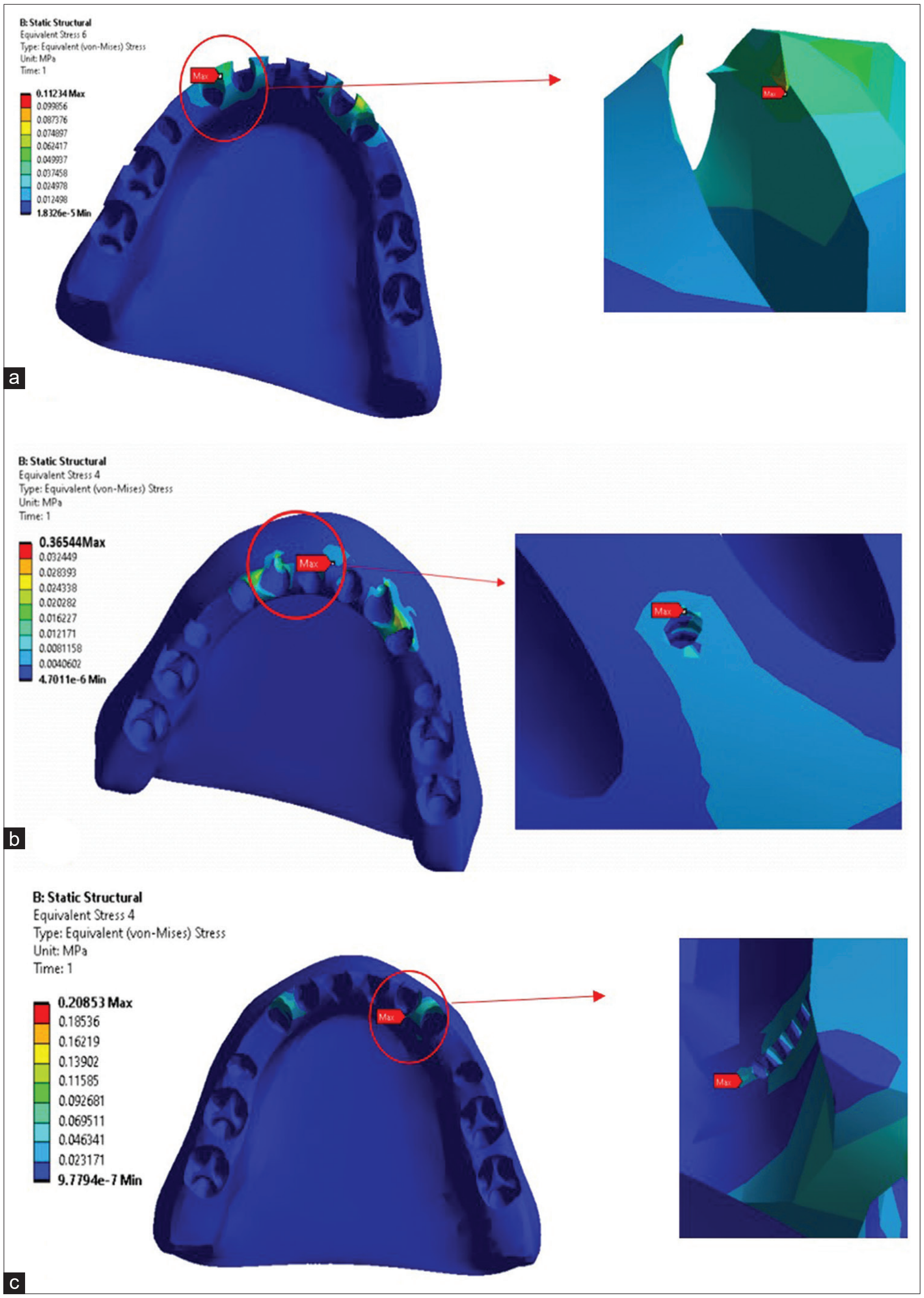

Figure 5: Maximum von Mises stress in cancellous bone in (a) two mini-implant, (b) three mini-implant and (c) four mini-implant model

Stress in teeth

Stresses on the teeth showed more stress on the lateral incisor among all anterior six teeth in all three groups. As the surface area and volume of the lateral incisor were less as compared to the central incisor and canine, the lateral incisor experienced the maximum stress. This was also supported by the study conducted by Masahiro[16] and Namburi *et al.*,[5] who also found similar results.

The maximum amount of stress was observed in the lateral incisor of the three mini-implants model as compared to the four mini-implants model with the least amount of stress in the two mini-implants model [Figure 9]. This same pattern was also observed in the central incisor. There was the addition of vertical force in the three and four mini-implants model, which increased the stress when compared to the two mini-implants model which has only horizontal force. In contrast to this, the canine in the four mini-implants model showed the maximum stress followed by three mini-implants with the least amount of stress in the two mini-implants model. This might be because there was a change in the

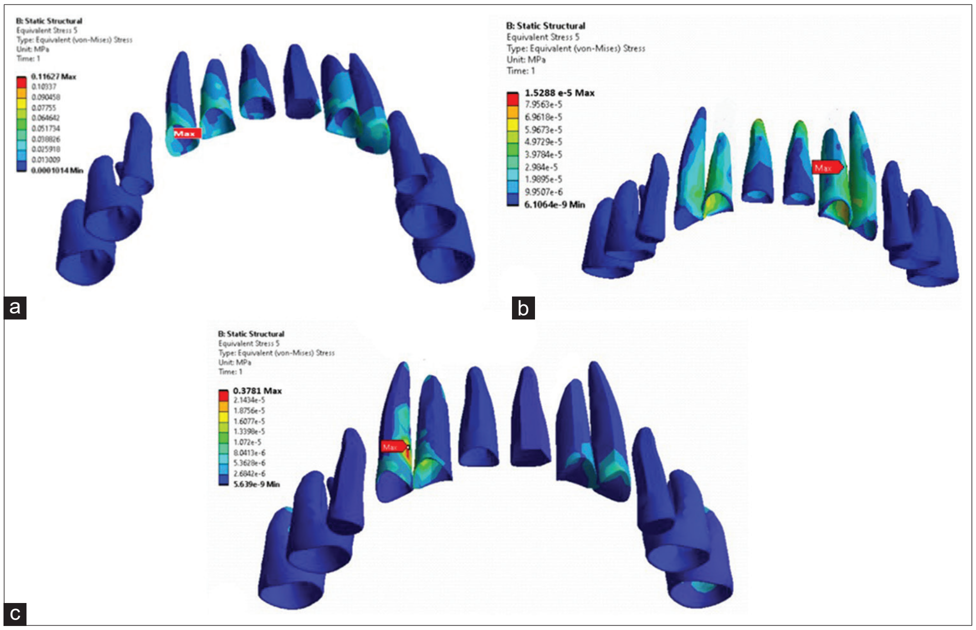

Figure 6: Maximum von Mises stress in periodontal ligament in (a) two mini-implants, (b) three mini-implants and (c) four mini-implants model

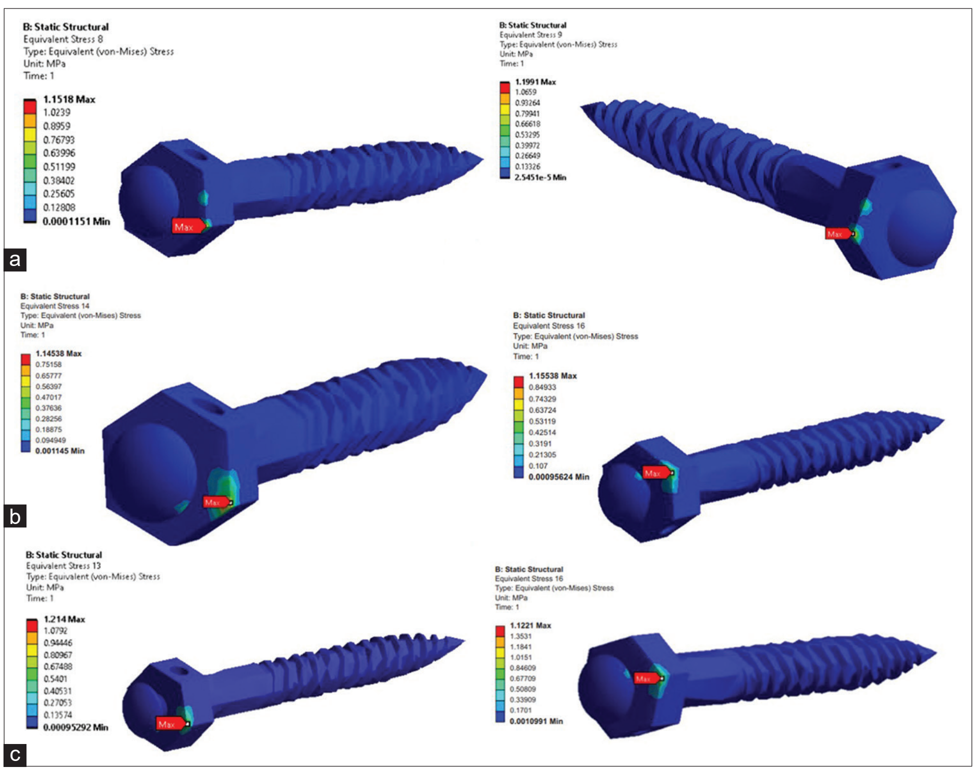

Figure 7: Maximum von Mises stress in posterior right and left mini-implant in (a) two mini-implants, (b) three mini-implants (c) and four mini-implant model

position of mini-implants as in the four mini-implants model the mini-implant are in more vicinity to canine as compared to the three mini-implant model in which the mini-implant was placed in between the central incisors. Also, in the three mini-implant model, there was less stress on the canine as it still showed extrusion which means there was little effect of vertical force on the canine whereas, in the four mini-implant model, the canine showed intrusion as the mini-implants were placed in between lateral incisor and canine.

Limitations of the study

The current finite element study presents some limitations that make it impossible to simulate clinical experiments exactly.

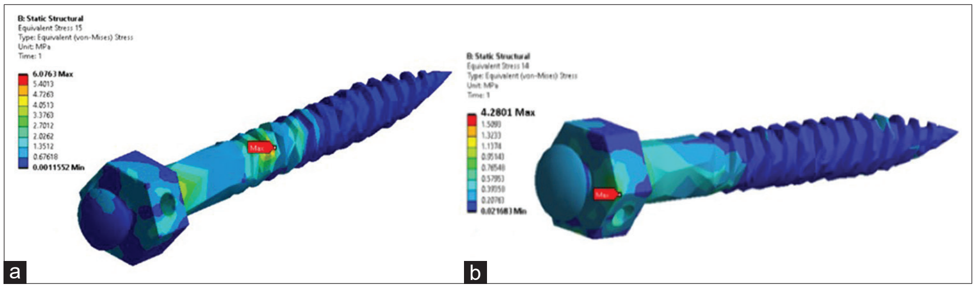

Figure 8: Maximum von Mises stress in anterior mini-implant in (a) three mini-implants and (b) four mini-implant model

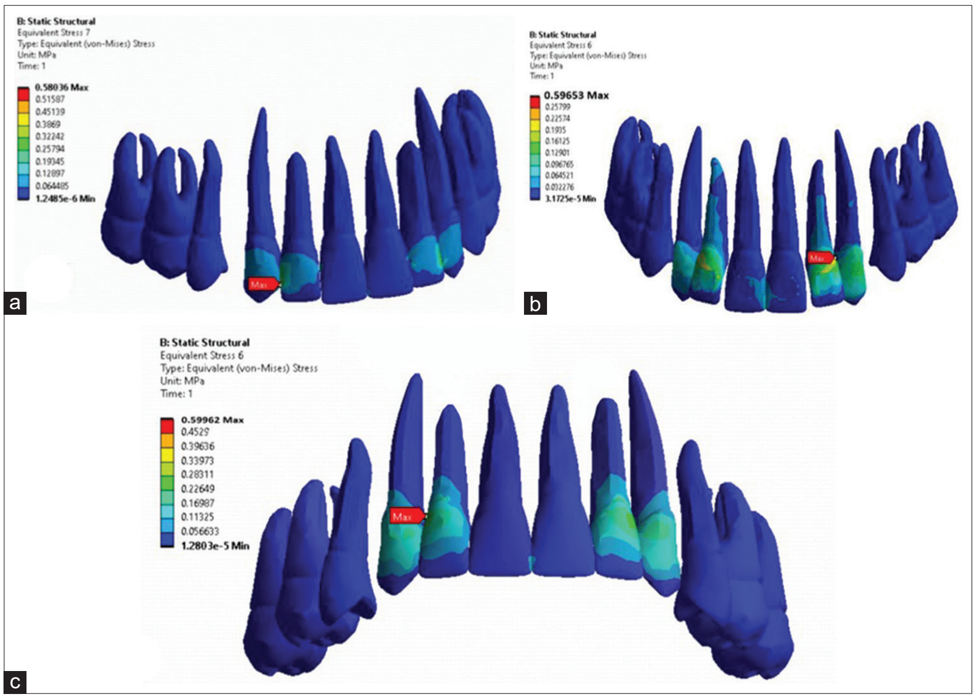

Figure 9: Maximum von Mises stress in anterior teeth in (a) two mini-implants, (b) three mini-implants and (c) four mini-implant model

1. Analytical results of FEM are highly dependent on the models developed; therefore, they have to be constructed to be equivalent to real objects in various aspects. The results of this study were obtained from simulated models, from which biological variabilities may occur.
2. The FEM can only calculate initial tooth displacement and stress distribution after force application. The biological and time-dependent reaction is still unpredictable and requires more clinical evidence.
3. During treatment, even with perfect mechanics and accurate force systems, after the initial tooth movement, the biomechanical effect of the force system changes, and modifications are required which is not possible with the FEM.

Conclusion

The following important conclusions are drawn from this study-

1. In all three models, it was observed that the displacement pattern in the sagittal plane showed the maximum amount of retraction in the two mini-implant model followed by the three mini-implant model with the least amount of retraction observation in the four mini-implant model.
2. In all three models, it was observed that the displacement pattern in the vertical plane showed the extrusion of maxillary six anterior teeth in the two mini-implant model, whereas the intrusion of central and lateral incisors was observed along with the extrusion of canine in the three mini-implant model. In contrast, intrusion of the maxillary six anterior teeth was observed in the four mini-implant model.
3. In all three models, it was observed that the maximum amount of von Mises stress in cortical bone, cancellous bone, PDL, and in maxillary four anterior teeth was observed in the three mini-implants model followed by four mini-implants with the least amount of stress in the two mini-implant model. In contrast, canines show the maximum stress in the

four mini-implant model, followed by the three mini-implant model with the least amount of stress in the two mini-implant model. The lateral incisor teeth showed the maximum von Mises stress in all six anterior teeth in all three models.

4. In all three models, the von Mises stress in posterior mini-implants was almost the same. The stress in anterior mini-implants was the maximum in the three mini-implants model as compared to the four mini-implants model.

This study suggests that the four mini-implant model was better than the three and two mini-implant models for simultaneous en-masse retraction and intrusion of maxillary anterior teeth as there was a more evenly distribution of force in the four mini-implants model as compared to the three mini-implant model.

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Conflicts of interest

There are no conflicts of interest.

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