"Comparative evaluation of incisal edge and root apex displacement in upper anterior teeth during torque movement using clear aligners with mini-implant placement - a three dimensional Finite Element Analysis"

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Abstract:
Background-This finite model element (FEM) study was carried out to determine the predictable displacement at the incisal edge and the root apex of upper incisor teeth through clear aligners and mini-implants among premolar extraction patients and to explore the effects of stress distribution on these tooth movements.
Objective- To assess the variations in stress concentration on the periodontal ligament (PDL) and evaluate the expected displacements of incisal edge & root apex between upper anterior six teeth for palatal root torque movement using clear aligner (CA) and mini-implants.
Materials and methods- An observational in-vitro study was conducted. A cone beam computed tomography (CBCT) scan of the upper jaw with extracted first premolars was obtained for precise imaging. Two 3D geometric FEA models were constructed with two distinct positions associated with the clear aligners and mini-implants. These models were transferred to Ansys software for analysis, which enabled the determination of displacement values at both the root apex and incisal edge in two axes (Y and Z).
Results- The CBCT images of premolar extracted upper jaw were analysed using Ansys software for the distribution of stress and displacement at incisal edge and root apex for all 6 upper anterior teeth. The results projected that Model 1 produced significantly higher overall stress values in all six anterior teeth analysed.
Conclusions- The analysis suggests that Model 1 (CA and mini-implants distal to lateral incisors) is ideal for maximizing incisal edge and root apex displacement along with palatal root torque movement, while Model 2 (CA and mini-implants distal to central incisors) is less suitable for achieving palatal root torque movements.
Keywords- CAT, continuous tooth movement, Finite Element (FE), mini screw implant, Clear aligners

Introduction-

Orthodontic practice routinely involves the extraction of premolar teeth, followed by the retraction of incisors. This process requires a precisely engineered biomechanical design that must include adequate intrusion and effective palatal root torquing of the incisors. The Clear Aligner Treatment Complexity Assessment Tool (CAT-CAT), a recently developed method for evaluating treatment complexity in clear aligner therapy, unequivocally identifies these specific tooth movements as particularly challenging.[1] For patients who undergo premolar extractions, the anticipated tooth movements are often unpredictable, leading to substantial discrepancies between expected and actual outcomes. This study underscores the critical importance of meticulous planning and execution in orthodontic treatment.

Recent advancements in orthodontic materials and innovations in biomechanics have contributed to the increasing acceptance of clear aligner therapy (CAT) among orthodontists and patients, primarily due to its aesthetic appeal and comfort. However, it is important to acknowledge that certain complex tooth movements, particularly bodily movement, and root torquing, may be challenging to achieve with CAT. Continued exploration and refinement in this field are essential to enhance the effectiveness of CAT and expand its application in addressing diverse orthodontic cases.[2,3]

Finite element (FE) simulation has become an invaluable tool for studying the behaviour of physiological units, regardless of their complexity. It allows for the analysis of changes in biomechanical behaviour that occur following the implantation of a prosthesis or osteosynthesis, as well as the biological reactions of bone in response to these changes. One significant advantage of FE modelling is its ability to predict alterations in stress distribution around implanted areas. This predictive capability can help prevent future complications arising from improper positioning or fixation of the prosthesis.[4]

The aim of this study was to evaluate and compare the displacement of incisal edge and root apex in upper anterior teeth during torquing movement utilizing clear aligners with mini-implants through finite element analysis (FEA).

Material and methods-

A single subject was selected from the Department of Orthodontics and Dentofacial Orthopaedics at People's Dental Academy in Bhanpur, Bhopal. A cone beam computed tomography (CBCT) scan was performed on a healthy individual's upper jaw with increased axial inclination of upper anterior teeth who had previously undergone premolar extraction, utilizing a KODAK imaging system from Carestream Health (Rochester, NY, USA). The three-dimensional reconstruction of the images was meticulously analysed using CS 3D Imaging software (version V-3.10.45), with a voxel size of 150µm. These detailed CBCT scans were subsequently utilized to construct finite element method (FEM) models, using HyperMesh software (version 11, Altair Engineering Inc., USA).

Material used-

All maxillary teeth with extracted 1st premolars, a Cone Beam Computed Tomography (CBCT) scan -KODAK imaging system from Carestream Health (Rochester, NY, USA), HyperMesh software (version 11), Altair Engineering Inc., USA) and ANSYS software (version 18.1, ANSYS Inc., Southpointe, Pittsburgh, USA), clear aligner, mini-implants, and E-chains.

Construction of FE models-

FEM is a method used to represent geometry through a finite number of elements and their connection points, referred to as nodes. These elements form the essential building blocks of the numerical representation of the model.

Construction of Geometric model-

The geometric modelling phase aims to represent geometry using points, lines, areas, and volumes. Complex objects can be simplified into geometrically simple elements. This is achieved through 3-D laser scanning technology, commonly used for modelling inanimate objects, including craniofacial structures such as the maxilla and mandible. During the conversion of geometric model into finite element model, discretization process divides a problem into smaller elements connected by nodes, ensuring matrix connectivity and reducing computing time. Elements can be one, two, or three-dimensional, and joining at key points is called 'meshing'.

Grouping of FE models-
After the construction of geometric 3D FEM models, they were divided into two groups for further analysis, namely-
Model 1: Comprising clear aligner with mini-implants positioned distal to lateral incisors and E-chains (type 1).
Model 2: Comprising clear aligner with mini-implants positioned distal to central incisors and E-chains (type 2).

In material properties and data presentation process equations are formulated for each element in the FEM mesh and then assembled into a set of global equations that represent the properties of the entire system. The basic material properties required are the poisson ratio and young's modulus, MPa.

Table 1- Properties of the materials taken in this study-

Material	Young's modulus, MPa	Poisson ratio
Alveolar bone	1.37×10^3	0.3
Tooth	1.96×10^4	0.3
PDL	6.9×10^{-1}	0.45
Aligner	816	0.36
Attachment	12.5×10^3	0.36
Titanium	15.5×10^6	0.35

Defining the Boundary Conditions: Boundary conditions refer to the constraints applied to an element constructed on a computer. When a force is applied to this element, it behaves like a free-floating rigid body, undergoing translational or rotational motion, or a combination of both, without experiencing any deformation. To analyse its deformation, it is necessary to restrict certain degrees of freedom — specifically, the movement of nodes in each direction (X, Y and Z) for some nodes. These constraints are known as boundary conditions. The study of force application at various points in geometric configurations is essential for understanding their structural behaviour is known as loading configuration.

Results-
The assessment of stress distribution along the periodontal ligament was conducted decisively for both models: equipped with CA and with mini-implants. Utilizing advanced analysis tools, such as HyperMesh software (version 11, Altair Engineering Inc., USA) and ANSYS software (version 18.1, ANSYS Inc., Southpointe, Pittsburgh, USA), were obtained crucial insights into stress performance. The results indicated that Model 1 produced significantly higher stress values in the six maxillary anterior teeth analysed. With an average stress value measured, model 1 displayed stress distribution in the maxillary anterior teeth at 0.11286 MPa, whereas

model 2 demonstrated the stress distribution measured at 0.10421 MPa, as shown in ***figures 1 and 2***. These figures represent the colour map where blue colour represents lowest stress strength and red colour represents highest stress strength. These findings are detailed in ***Tables 2 and 3***. In model 1, the upper central incisors, lateral incisors, and canines experienced the von mises stress, measured at 0.114465 MPa, 0.126755 MPa, and 0.0988 MPa, respectively, whereas in model 2, the upper central incisors, lateral incisors, and canines experienced the von mises stress, measured at 0.10674 MPa, 0.117375 MPa, and 0.0901 MPa, respectively, highlighting the superior efficacy of model 1 in comparison to model 2.

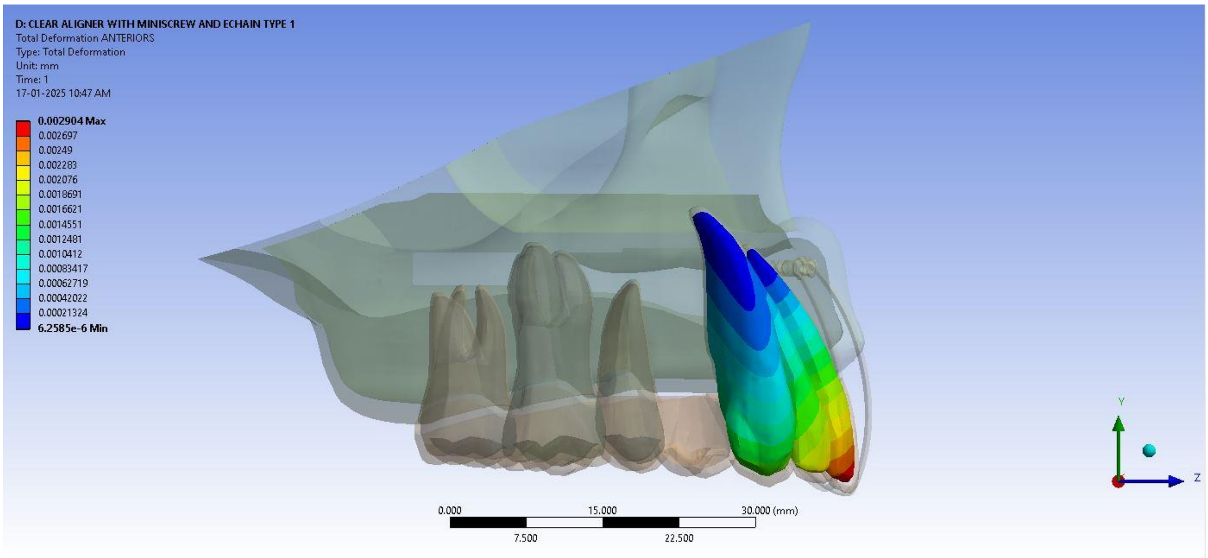


Figure 1: Depicting von mises stress (in MPa) for model 1 (CA and mini-implant with distal to lateral incisors).

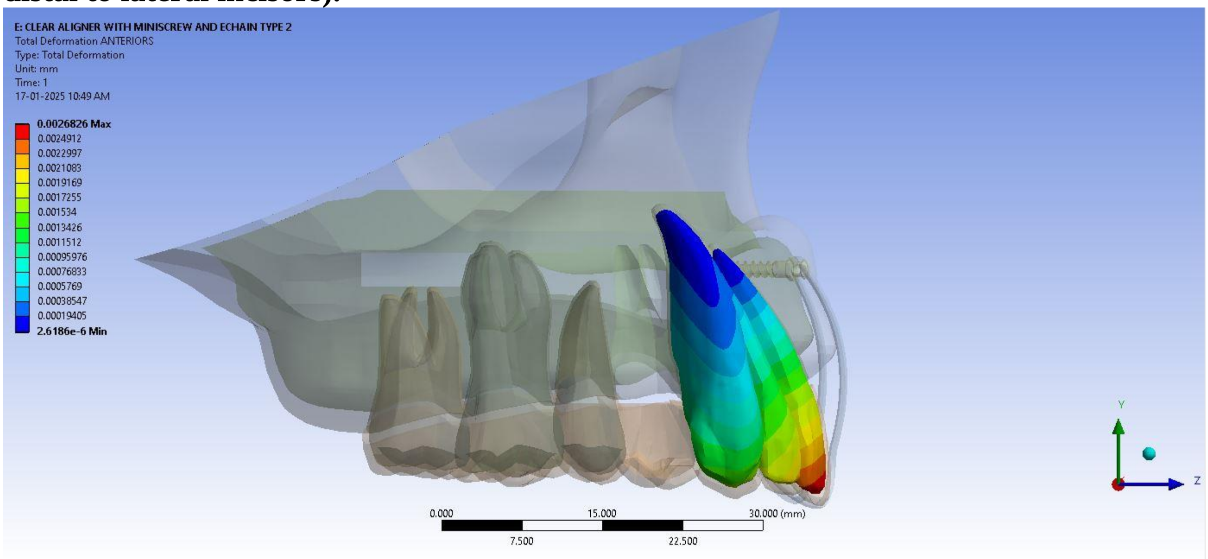


Figure 2: Depicting von mises stress (in MPa) for model 2 (CA and mini-implant with distal to central incisors).

In the FEM simulation of incisal edge and root apex displacement, model 1 demonstrated greater displacement at the incisal edge and root apex of the central incisors, lateral incisors and canines compared to model 2. In model 1, the recorded displacement of incisal edges were 0.0028354 mm, 0.0021627 mm, and 0.00169045 mm, respectively, while the root apex displacements were 0.00001539 mm, 0.0010966725 mm, and 0.000109325 mm, respectively. Conversely, model 2 demonstrated displacement in overall upper anterior six anterior teeth, with the incisal edge displacements measured at 0.0026224 mm, 0.00203685 mm, 0.00160585 mm, respectively, while the root apex displacement were 0.000015404 mm, 0.0000321705 mm, and 0.00010548 mm respectively, as detailed in ***Table 4***. These findings provided the displacement of the constructed 3D geometric finite element models when a uniform force of 7.9 Nmm with 100g of elastic force each directed bilaterally towards the mini-implant was applied.

Table 2: Stress distribution of model 1: Clear aligner with mini-implant positioned distal to lateral incisors and E-chain (type 1)-

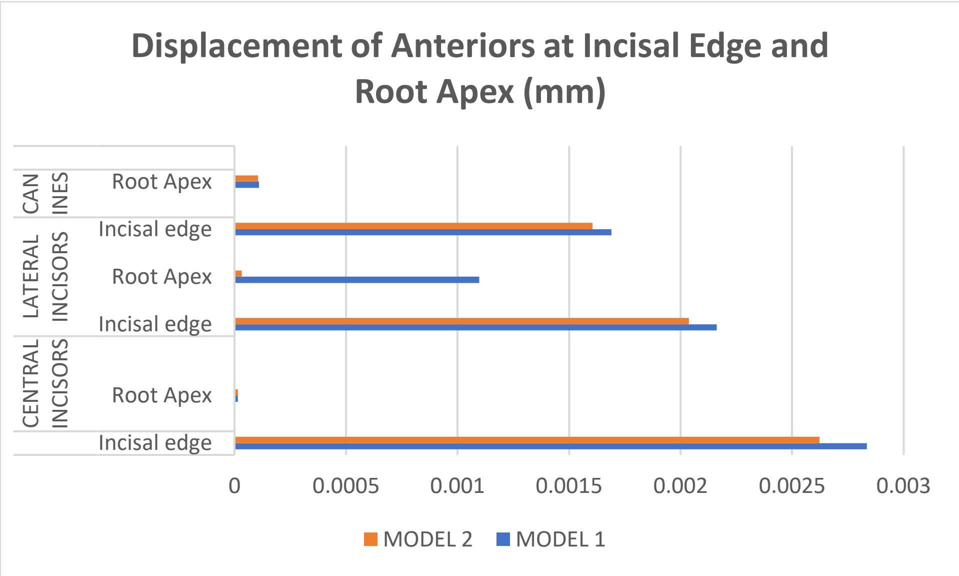
ENTITY	AVG VON MISES STRESS (MPa)
CENTRAL INCISORS	0.114465
LATERAL INCISORS	0.126755
CANINES	0.0988
ANTERIORS (6 TEETH)	0.11286

Table 3: Stress distribution of model 2: Clear aligner with mini-implant positioned distal to central incisors and E-chain (type 2)

ENTITY	AVG VON MISES STRESS (MPa)
CENTRAL INCISORS	0.10674
LATERAL INCISORS	0.117375
CANINES	0.0901
ANTERIORS (6 TEETH)	0.10421

Table 4: Displacement of anteriors at incisal edge and root apex (in millimetres)

TOOTH	POSITIONOF COORDINATES	MODEL 1	MODEL 2
CENTRAL INCISORS	Incisal edge	0.0028354	0.0026224
	Root Apex	0.00001539	0.000015404
LATERAL INCISORS	Incisal edge	0.0021627	0.00203685
	Root Apex	0.0010966725	0.0000321705
CANINES	Incisal edge	0.00169045	0.00160585
	Root Apex	0.000109325	0.00010548



Graph 1: Displaying highest displacement tendencies of upper anterior teeth at incisal edge and root apex (mm) in comparison (Blue – Model 1, Orange – Model 2)

Discussion-

FEM can be used to address the internal stress-strain relationships, especially in hard tissue structures of the human body. This technique offers the ability to create mathematical models that accurately represent real objects with complex shapes and a variety of materials. Thus, due to its detailed three-dimensional geometry, FEM is an ideal method for precise modelling of the tooth and periodontium.[5,6] The 3D FEM makes it possible to visualize forces applied mechanisms and analyse how the jawbone reacts to loads in three dimensions.[7,8]

The current study focused on the advanced use of clear aligners and mini-implants positioned at two distinct locations: distal to central incisors and distal to lateral incisors. The displacement of upper six anterior teeth at incisal edge and root apex was calculated with the constructed 3D finite element models when a uniform force of 7.9 Nmm with 100g of elastic force each directed bilaterally towards mini-implants was applied. After FEM simulation was performed, the results showed that model 1 (CA with mini-implants distal to lateral incisors) demonstrated highest displacement at the incisal edge of the central incisors, lateral incisors and canines compared to Model 2 (CA with mini-implants distal to central incisors), with a recorded displacement of 0.0028354 mm, 0.0021627 mm, and 0.00169045 mm, respectively. Conversely, Model 2 exhibited a least displacement in overall anterior teeth except in the region surrounding the central incisors, which showed increased displacement at root apex measured at 0.000015404 mm. These findings also suggest that CA with mini-implants distal to lateral incisors exhibited higher displacement both incisal edge and root apex region, therefore indicated for maintaining better torque control seen during intrusion, while clear aligner with mini-implants positioned distal to central incisor, demonstrated least incisal edge displacement and root apex displacement except for higher root apex displacement were observed in central incisors, indicating an overall loss of torque expression in upper anterior teeth during intrusion. According to Liu et al.[9] CAT resulted in lingual tipping and extrusion of incisors during anterior retraction. Incisors intrusion and palatal root torque was achieved with anterior mini-screws and elastics. Linguoincisal elastics were superior to labial elastics suggesting less occurrence of buccal open bite. Similar results were confirmed in the present study when clear aligner along with mini-screws showed better torque movement during intrusion of upper incisors. However, in this study two mini-implants were used at two distinct positions at similar heights instead of single mini-implant. The elastics applied in both the models were from linguoincisally which demonstrated uniform distribution of forces. The results showed that clear aligner with mini-implants located distal to lateral incisors in comparison to mini-implants located to distal to centrals were better with torque movement with higher displacement values measured at incisal and root apex region respectively, when intrusive forces were applied.

A study undertaken by Xiao et al.[10] investigated the effectiveness of different modes of intrusion of maxillary anterior teeth with three kinds of mini-implant site were designed in clear aligner treatment using finite element analysis. The results demonstrated that the labiolingual angulation of maxillary anterior teeth exhibited positive intrusion changes under all conditions, with greater changes were observed under linguoincisal loading. The results of the present study also agree with intrusion observed with increased labiolingual angulation of maxillary anterior teeth analysed using two different mini-implant locations in clear aligner with palatal root movement displacement tendencies at incisal edge and root apex when calculated. Therefore, it is necessary to conduct further investigations including different locations within this area to interpret the implications for orthodontic treatment and to ensure optimum outcomes for dental health.

By comparing the findings with previous studies, this study found that anterior placement of two mini-implants with clear aligners can effectively achieve incisor intrusion and palatal root displacement which enhanced the understanding of stress concentration and displacement outcomes.

Limitations-

The limitations of this study were: while FEM offers an effective and high degree of accuracy while maintaining a non-invasive nature, which allows for precise control over study variables, however, the results may not be similar and vary from those of in vitro study and clinical studies, because of the difference in the oral environment and presence of anatomical limitations. The generated values after FEA simulation must be clinically confirmed to reinforce the effects in relation to clear aligners with mini-implants.

Conclusions-

1. The analysis highlights that clear aligner with mini-implant positioned distal to lateral incisors was more effective in maximizing both incisal edge and root apex displacement while, clear aligner with mini-implant positioned distal to central incisors resulted in least displacement.
2. The study confirmed a valuable insight that combining clear aligner with mini-implants when positioned near the upper incisors optimizes both palatal torque movements and incisal edge displacement during intrusion for individuals with extracted premolars.

Hence, this approach holds acceptable potential for improving predictability of using clear aligner and mini-implants for maintaining ideal axial inclination and torque control at the time of intrusion as orthodontic tooth movement.

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