The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 20(3): S.I(3). 1960-1977, 2025 www.thebioscan.co

Comparative evaluation of stress distribution between clear aligners and fixed appliance with and without mini-implant placement during intrusion of maxillary anterior teeth- A 3-dimensional finite element analysis

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DOI: 10.63001/tbs.2025.v20.i03.S.I(3).pp1960-1977

KEYWORDS
Orthodontics, Gummy smile, Intrusion, conventional brackets, clear aligners,mini-screws,TADs, PDL hydrostatic pressure-Periodontal ligament, Von misses stress.

Received on:
22-08-2025
Acceptedon:
20-10-2025
Publishedon:
29-11-2025

ABSTRACT
Aim – The present study is a FEM study assessing the amount of stress on periodontal ligament of tooth (von misses stress) during intrusion of maxillary anterior teeth for correction of gummy smile using clear aligners and conventional brackets with and without the use of mini-implants.

Materials and methods – Cone Beam Computerized Tomography (CBCT) scan which were obtained from DENTSPLY Sirona Ortophos SL 80kv 9500 cone beam 3D Extra oral imaging system with are construction volume of 50x37 mm and are constructed matrix voxel of 0.2x0.2x0.2 um. The equipment had CMOS (Complementary Metal Oxide Semiconductor) sensor technology. The field ofview was 11 x 10 mm, exposure parameters for the patients varied from 70k V8mA with a scan time of 14 seconds. All the teeth were assessed by the 3D volume tricimage and 1 mm tomographic sections in sagittal, axial and coronalplanes.
Result – The least amount of stress on PDL of tooth (von misses stress) during intrusion of maxillary anterior teeth was seen conventional appliance and mini-screws and the maximum amount of stress on PDL (von misses stress) of tooth was seen along with conventional brackets with burstone intrusion arch.
Conclusion – Gummy smile correction using clear aligners and e-chain is the best treatment modality among all four models in planning maxillary anterior intrusion.

INTRODUCTION

One of the ultimate goals of orthodontic treatment is to achieve an attractive smile. A beautiful smile must have a consonant smile arc, ideally with proportionate tooth sizes and a harmonic gingival line. However, a "gummy smile," or excessive gingival show during a smile, is seen as a drawback for aesthetics. Orthognathic surgery was often thought to be the only treatment for adult patients with gummy smiles. These days, adult patients can have their gummy grins fixed with periodontal surgery and skeletal anchorage, sometimes referred to as temporary anchorage devices (TADs) [1]

Excessive gingival show, sometimes known as the "gummy smile," is a cosmetic concern for dental patients because it is generally considered unpleasant and many of them seek treatment for it[1]. When there is more than 3 to 4 mm of gingival tissue showing when smiling, it gives the illusion of an uneven smile. Anatomical landmarks including the maxilla, lips, gingival structures, and teeth can all affect a gingival grin[1].

To create a lovely grin, all of these anatomical features must cooperate with one another[1]. Alterations in passive tooth eruption, dentoalveolar extrusion, vertical maxillary excess, hyperactive or short upper lip muscles, or a combination of these can all cause a gummy grin [2]. Modified passive eruption can be corrected with crown lengthening surgery, which is achieved via gingivectomy or a flap placed apically. Botulinum toxin injections are a nonsurgical treatment option for gummy grins that are mainly brought on by hyperactive upper lips[3].

However, it is far more difficult to treat gummy grins caused by dentoalveolar and maxillary height aetiologies. In the past, the only treatment for dentoalveolar extrusion and increased maxillary height was orthognathic surgery, which is an intrusive process[3]. However, it has been seen that gummy grins caused by increased maxillary height and dentoalveolar extrusion may occasionally be repaired with the invention of temporary skeletal anchoring devices (TADs)[3, 4].

According to some case reports, a mini-screw can be used to correct a gummy smile with the full incursion of the maxillary arch, which can have the same result as maxillary impaction with Le Fort I surgery[5]. Dental intrusion is often an essential part of orthodontic treatment because it improves the incisors' sagittal and vertical relationships, corrects the angle between the incisors and the gingival line, and restores the smile's aesthetic attractiveness[6].

Burstone defines intrusion as the apical movement of the geometric radicular center with res pect to the occlusal plane or a plane defined by the long axis of the tooth, whereas Nikolai defines it as a type of translational tooth movement that moves apically along the longitudin al axis of the tooth [7–9].

The upper and lower lips frame the smile. Within this framework, the components of a smile are the teeth and the gingival scaffold[6–8]. There are three types of lip lines that show up when you smile: low, medium, and high.

The lip line is low when there is no gum showing when you smile. The lip line is medium when there is 1-3 mm of gum visible during a grin; it is high when there is more than 4 mm of gingival display during a smile, which is known as a gummy smile.

With the exception of a few case reports, little study has been done on the significance of using mini-implant absolute anchorages to fully invade the arch and repair the gummy grin brought on by dentoalveolar extrusion and vertical maxillary excess[3–5]. Thus, our goal was to use TADs to simulate four distinct full arch intrusion strategies for the first time and investigate their dynamics, effectiveness, and possible drawbacks (e.g., the risk of root resorption, which is indicated by an excessively high PDL hydrostatic pressure that can collapse the capillaries and impair blood flow[10, 11].

Orthodontic research has made extensive use of the Finite Element Method (FEM), an engineering technology used to compute stress and deformation of complex structures.
FEM offers the benefit of being a precise, non-invasive technique that yields quantitative, in-depth information on potential physiological reactions in tissue. The visualisation of these reactions can be predicted using the FEM by looking at the areas of stress created by applied orthodontic forces. When using various orthodontic device kinds, FEM may evaluate the distribution of stress at the interface between PDL and alveolar bone as well as the shifting trend in various tooth movement types. FEM is a legitimate and trustworthy method for forecasting the movement of teeth that will occur during orthodontic therapy[13].

MATERIALS AND METHODS

MATERIAL

1. Cone Beam Computerized Tomography (CBCT) scan which were obtained from DENTSPLY Sirona Ortophos SL 80kv 9500 cone beam 3D Extra oral imaging system with are construction volume of 50x37 mm and are constructed matrix voxel of 0.2x0.2x0.2 um. The equipment had CMOS (Complementary Metal Oxide Semiconductor) sensor technology. The field of

view was 11 x 10 mm, exposure parameters for the patients varied from 70k V8mA with a scan time of 14 seconds. All the teeth were assessed by the 3D volume tricimage and 1 mm tomographic sections in sagittal, axial and coronal planes.

2. 3D finite element models simulating

a) Maxillary arch containing Central Incisor, Lateral Incisor, Canine, Second Premolar, First and Second Molar with surrounding period on talligament and alveolar bone.

b) Brackets (0.022x0.028 slot dimensions) on each tooth (OSL M3), 0.019x0.025 Stainless Steel wire (OSL), TAD (1.6x8 mm), Aligner- PET G sheet(0.5 mm) and Power Chain (Ormco Gen 2).

3. Hyper Mesh software (version 11, Altair Engineering, Inc. USA). Hyper Mesh software is a multi-disciplinary finite element pre-processor software which imports STL file format of CBCT CAD-CAM images and processes these images to form meshed finite element models that can be used forvarious problem solving.

4. ANSYS software (version 18.1, ANSYS Inc, Southpointe, Pittsburgh (USA). ANSYS is a software which analyses the meshed finite element models and numerically solves various wide variety of mechanical problems like displacement of teeth when load is applied, stress distribution around the PDL strain energy etc.

METHODS

Exclusion Criteria:

1. Patient with pathologies.
2. Patient having prosthesis
3. Patient with compromised periodontal health.
4. Patient with congenitally missing teeth except for the 3rd molars.

Inclusion Criteria:

1. Patient with permanent dentition.
2. Patient with gummy smile (Gingival display> 4 mm)
3. Patients with deep bite.

A patient with gummy smile with deep bite was undergoing orthodontic treatment in People's Dental Academy's Orthodontics Department, a finite element analysis was performed to compare stress distribution between clear aligner and fixed appliance with and without the use of mini-implants during intrusion of maxillary anterior teeth. Approval for this study was granted by RAC & IEC from Peoples Dental Academy and Peoples University Bhopal. A CBCT of a maxilla with extracted first premolar was obtained from DENTSPLY Sirona Ortophos. In the process of finite element (FE) model construction the Digital Imaging and Communications in Medicine (DICOM) files exported from CBCT which were obtained from DENTSPLY Sirona Ortophos SL 80 kv 9500 cone beam 3D Extra oralimaging system with a reconstruction volume of 50x37 mm and a reconstructed matrix voxel of 0.2 x 0.2 x 0.2 um. The equipment had CMOS (complementary metaloxide semiconductor) sensor technology. Exposure parameters for the patients varied from 70k V8mA with a scan time of 14 seconds.The impacted teeth were assessed by the 3D volumetric image and 1 mm tomographic sections in sagittal, axial and coronal planes. The field of view was 11x10 mm (from the bottom of the chin to the top of the jaw).

All the images were visualized by Sirona Orthophos software on a standard. The DICOM files were converted to stereo lithography (STL) files using the Hyper Mesh software (version 11, Altair Engineering, Inc, USA). The 3D FE models consisted of unilateral maxillary quadrant from central incisor to second molar except first premolar and the constructed PDL for each tooth. The virtual PDL models were constructed around the root surface of each tooth with a 0.25mm, uniform thickness. Each model consisted of a cancellous bone surrounded by a 1mm thick cortical bone.

Defining the boundary condition

The boundary conditions were defined to simulate how the model would be constrained and to prevent it from free body motion. The nodes attached to the area of the outer surface of the bone were fixed in all directions to avoid free movements. At the connected nodes between the archwire and the brackets, translational degrees of freedom in the two flexural directions of the archwire was coupled to deform together, and translational degrees of freedom in the axial direction of the archwire was un constrained. The contact condition between each structure of the FE model was assigned as tie-contact constraint. The tie-contact constraint was defined as the contact between each part of the model being perfectly bonded, but the surface on each part being separated.

Virtual Models

MODEL 1: Conventional fixed appliance with burstone intrusion arch (Fig.1)

MODEL 2: Clear aligner with power ridge (Fig.2)

MODEL 3: Conventional fixed appliance with Two Mini-implants distal to central incisor (Fig.3)

MODEL 4: Clear aligner with Two Mini-implants distal to central incisors (Fig.4)

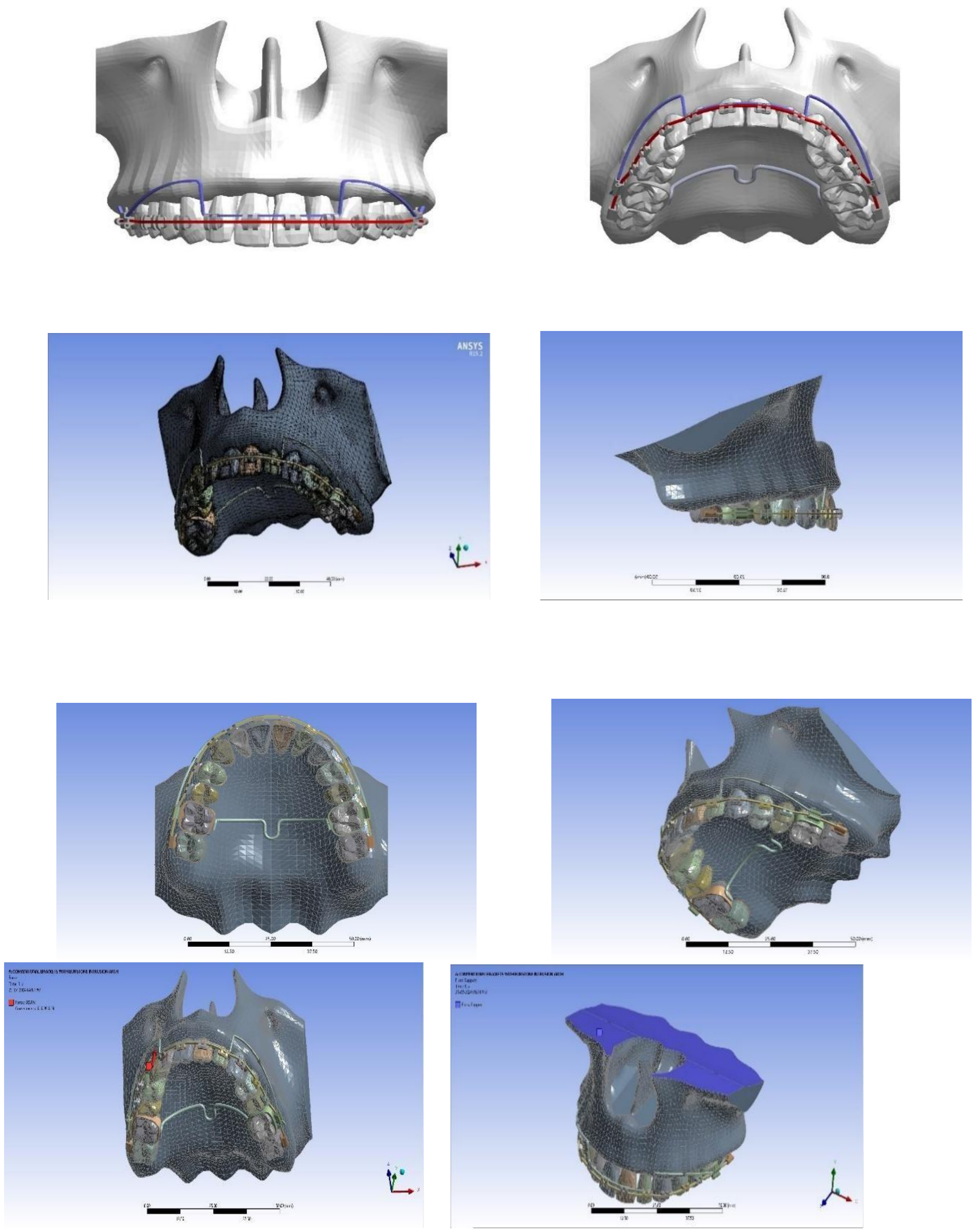
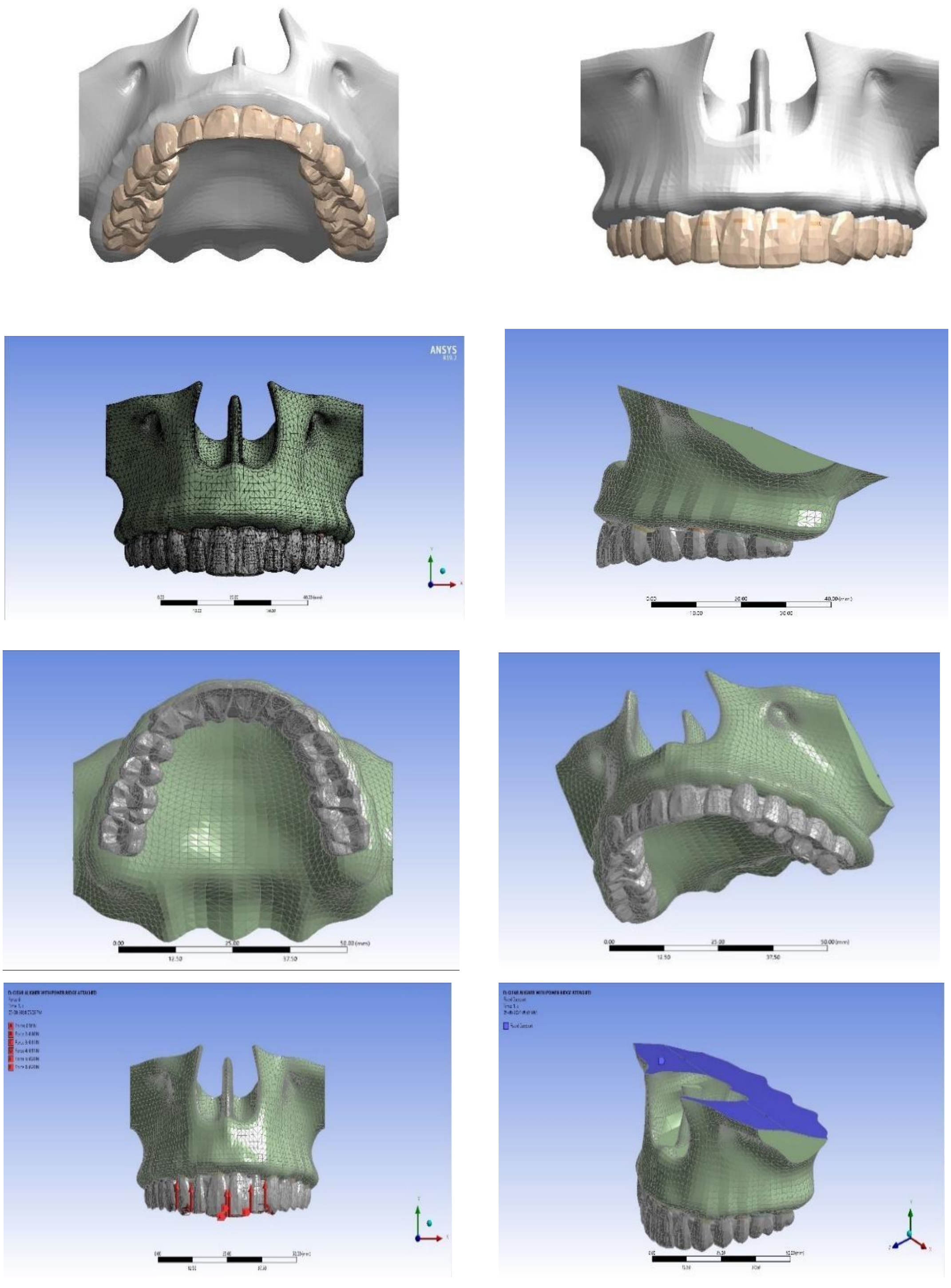


Fig.1: Conventional fixed appliance with burstone intrusion arch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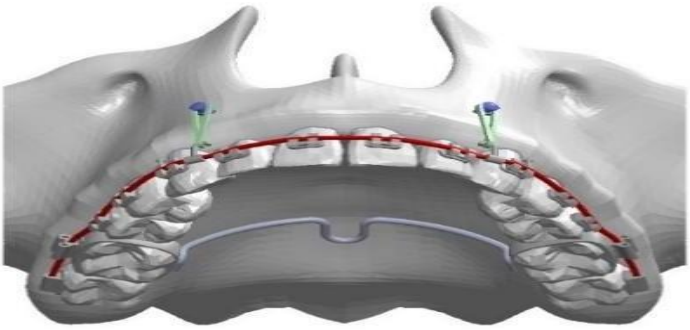

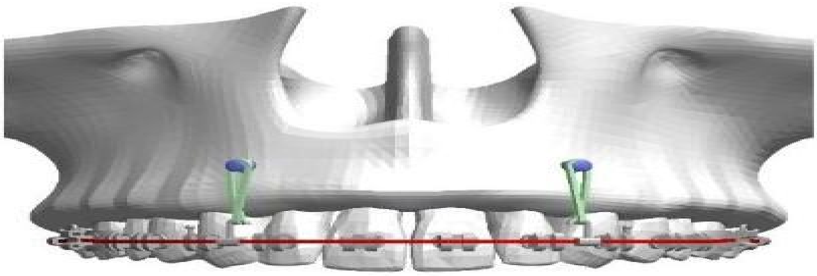

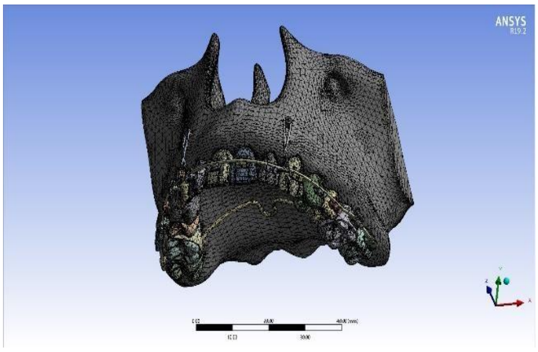
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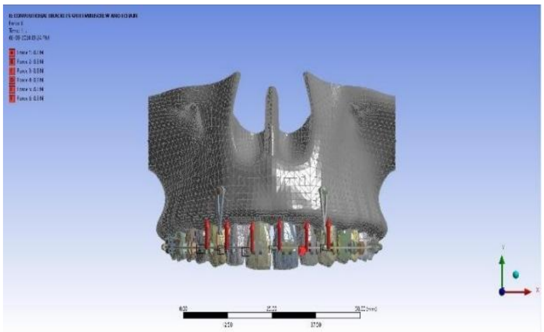
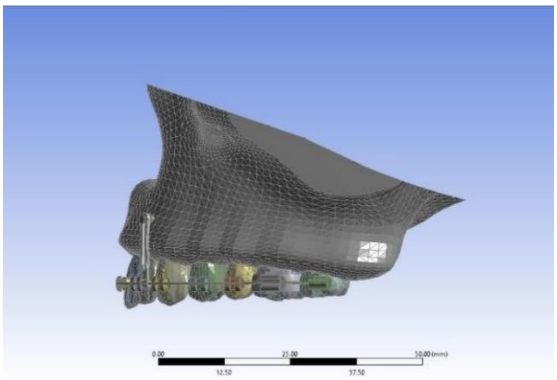
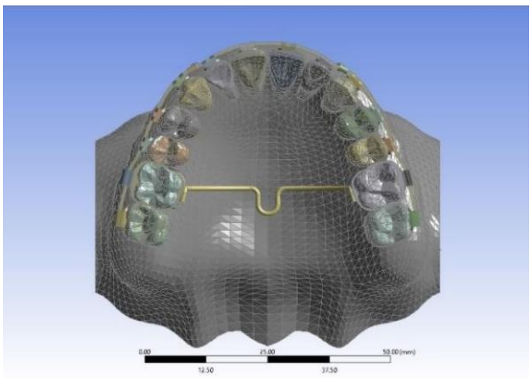






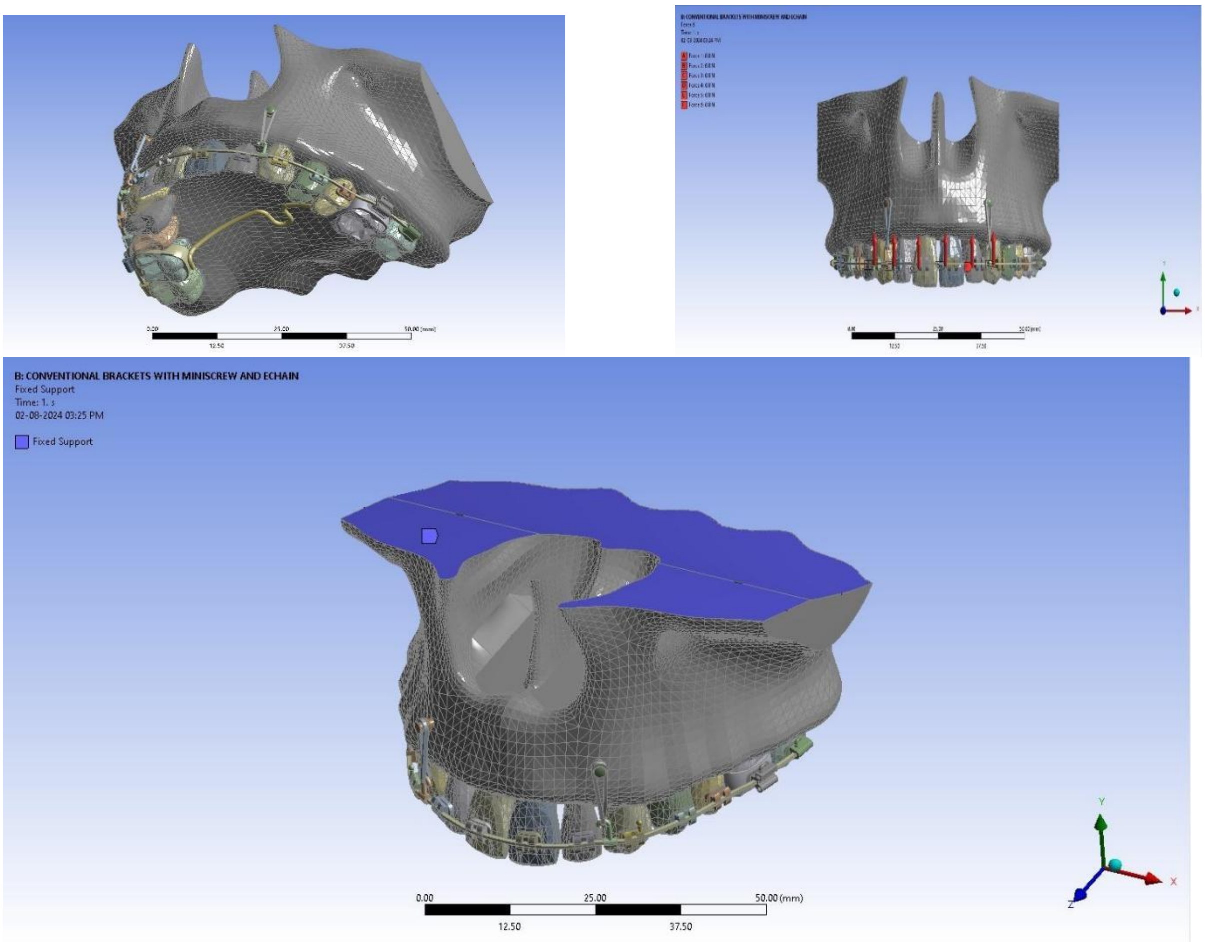
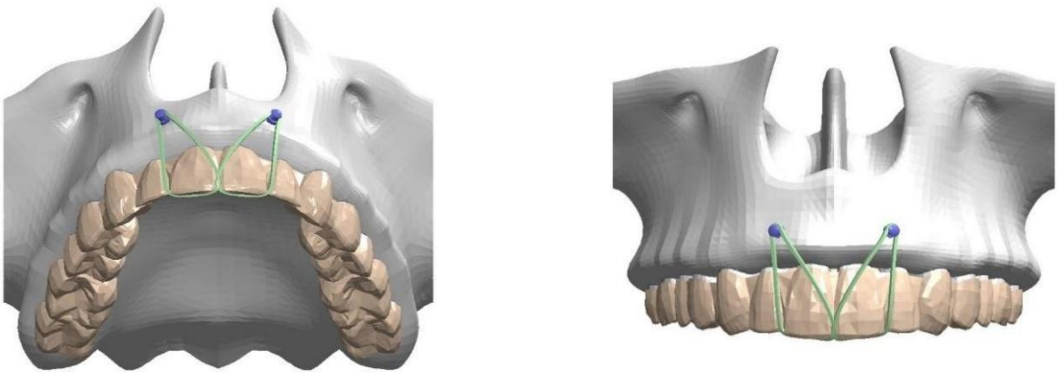


Fig.3: Conventional fixed appliance with Two Mini-implants distal to central incisors



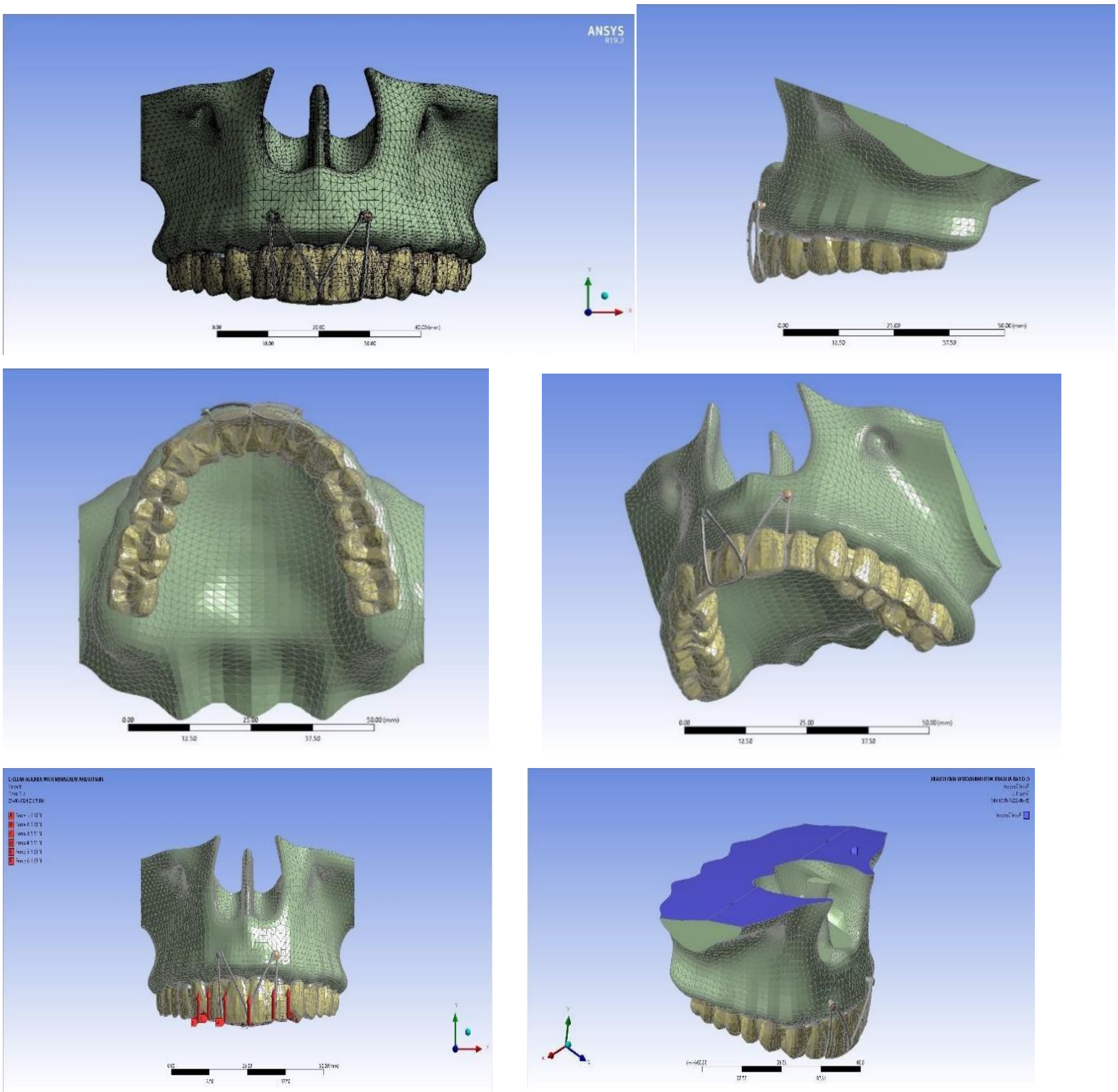


Fig.4: Clear aligner with Two Mini-implants distal to central incisors

MODEL 1: Conventional brackets (3M Unitec) along with banding of 1^{st} molars were done. The wire used was 0.019x0.025 stainless steel secured into brackets using 0.20 stainless steel ligation wire. TPA (Trans palatal arch) was placed engaging the 1^{st} molars made up of 0.9 stainless steel wire. Burstone intrusion arch (0.017x0.025 TMA) was placed distal to laterals for intrusion of maxillary anterior teeth. For intrusion of maxillary anterior teeth 100 grams of force was applied per side.

MODEL 2: Aligners (0.5 mm) were engaged to maxillary arch till 2^{nd} molar. Power ridge attachment was placed onto gingival 3^{rd} of the buccal surface of maxillary anterior teeth.

MODEL 3: Conventional brackets (3M Unitec) along with banding of 1^{st} molars were done. The wire used was 0.019x0.025 stainless steel secured into brackets using 0.20 stainless steel ligation wire. TPA (Trans palatal arch) was placed engaging the 1st molars made up of 0.9 stainless steel wire. TADs (1.6x8 mm) were placed distal to lateral incisors and connected to arch wire using 3.5 oz elastics.

MODEL 4: Aligners (0.5 mm) were engaged to maxillary arch till 2nd molar. TADs (1.6x8 mm) were placed distal to lateral incisors and connected to aligner cut present lingual to maxillary central incisor using 3.5 oz elastics.

Material properties

Materials in the models were assigned the properties explained in Table 1. A elastic chain was used for the intrusion of 3.5 ounces.

Material properties	Material Elastic modulus (MPa)	Poisson ratio
Cortical bone	1000	0.3
Cancellous bone	500	0.3
Dentine	18600	0.3
PDL	0.15	0.45
Stainless steel	200000	0.3
Miniscrew titanium G5	115000	0.33

Table 1.

Materials in the models were assigned the properties explained in Table 1. The simulated elastic chain was used of 3.5 ounces in Model 2 and Model 4.

Meshing

After applying the properties of the components, their meshing, which is one of the main parts of finite element analysis, was performed. To do this, the model was divided into smaller three-dimensional parts called elements, which were made up of a number of nodes. The total number of elements in all the models were 16,60,697 tetrahedral elements, and the number of nodes were 36,38,347.

NUMBER OF NODES AND ELEMENTS			
S.No.	CASE	NODES	ELEMENTS

1	CONVENTIONAL BRACKETS WITH BURSTONE INTRUSION ARCH	782380	429994
2	CLEAR ALIGNER WITH POWER RIDGE ATTACHED	874799	483853
3	CONVENTIONAL BRACKETS WITH MINISCREW AND ECHAIN	836150	482220
4	CLEAR ALIGNER WITH MINISCREW AND ECHAIN	1118018	651630

Table. 2

Boundary Conditions

In the next step, boundary conditions were applied: in this step, the fixed parts of the model were identified and forces were applied to the model. The maxilla was immobilized at its upper surface.

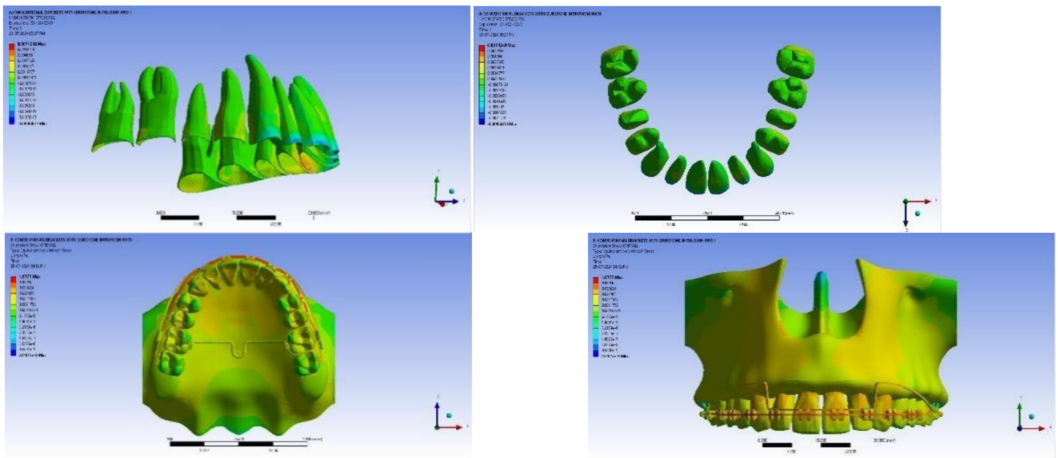
Outcomes

The duration for finite element simulations was 1 second. The created and loaded models were compared regarding displacement of PDL in x-axis, y-axis and z-axis.

STATISTICAL ANALYSIS

Data was entered in a Microsoft Excel spreadsheet and descriptive data were analyzed using SPSS software Version 26.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistics and the Wilcoxon signed-rank test were used to analyze the results. For statistical purposes, a p-value of ≤0.05 was considered significant.

RESULT



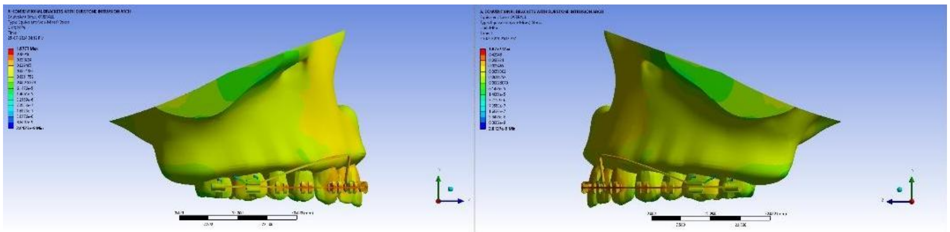


Fig 5. Overall equivalent stress and PDL hydrostatic pressure on teeth in conventional appliance with burstone intrusion arch

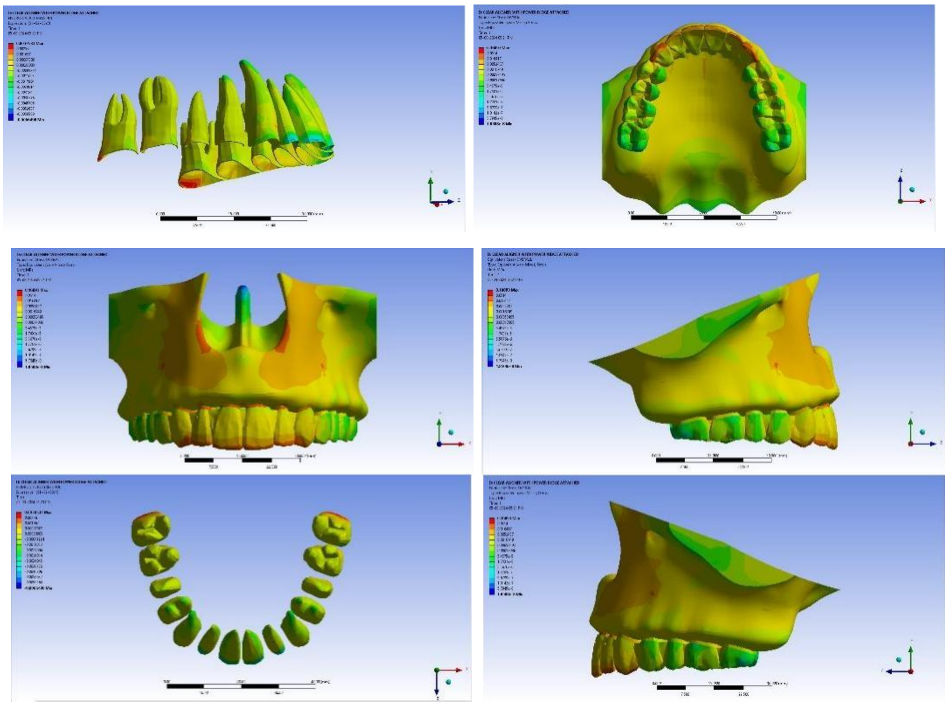
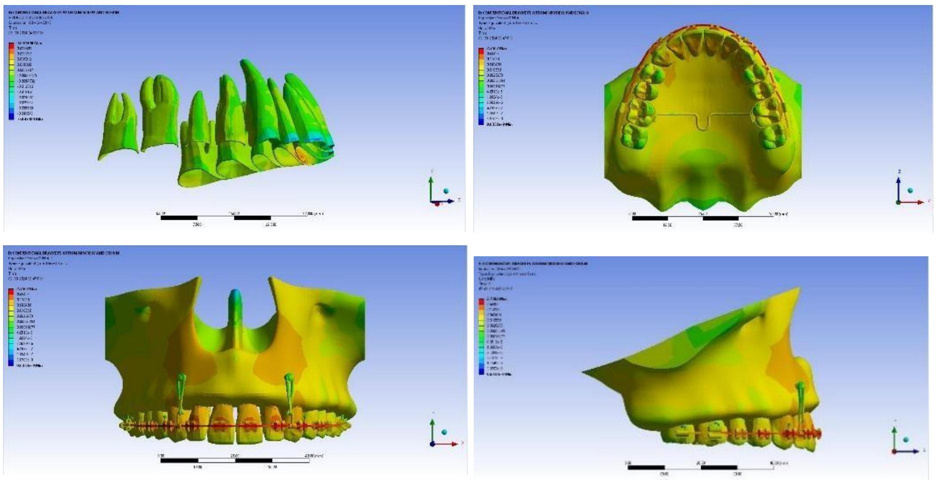


Fig 6. Overall equivalent stress and PDL hydrostatic pressure on teeth in clear aligner with power ridge.



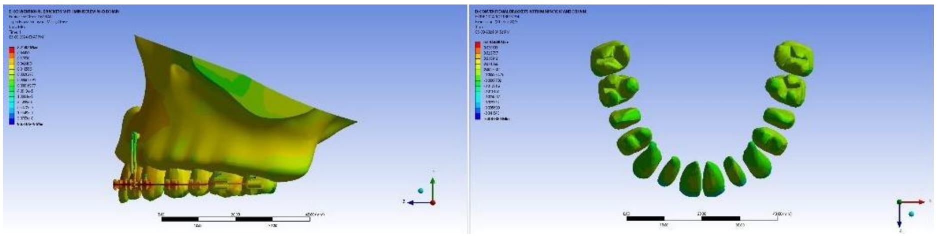


Fig 7. Overall equivalent stress and PDL hydrostatic pressure on teeth in conventional appliance with mini-implants.

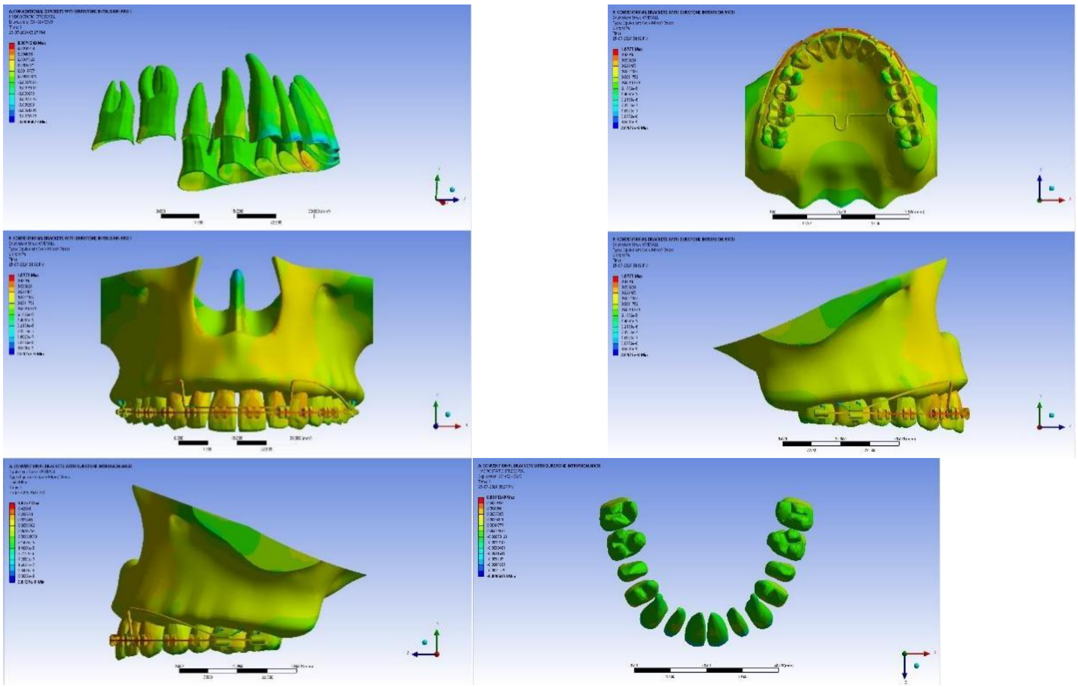


Fig 8. Overall equivalent stress and PDL hydrostatic pressure on teeth in conventional appliance with burstone intrusion arch.

CONVENTIONAL BRACKETS WITH BURSTONE INTRUSION ARCH
HYDROSTATIC STRESS ON PDL (MPa)

SR NO.	PDL		MINUMUM	MAXIMUM	AVERAGE
1	RIGHT	SECOND MOLAR	-9.50E-04	2.25E-03	1.27E-04
2		FIRST MOLAR	-6.63E-04	1.58E-03	5.10E-05
3		SECOND PREMOLAR	-7.41E-04	1.55E-03	1.43E-04
4		FIRST PREMOLAR	-1.70E-03	7.11E-03	1.89E-04
5		CANINE	-4.96E-03	5.99E-03	-4.37E-04
6		LATERAL INCISOR	-8.34E-03	2.53E-03	-7.13E-04
7		CENTRAL INCISOR	-8.69E-03	1.87E-03	-8.26E-04
8	LEFT	SECOND MOLAR	-9.02E-04	2.38E-03	1.26E-04
9		FIRST MOLAR	-6.93E-04	1.65E-03	4.92E-05
10		SECOND PREMOLAR	-7.45E-04	1.54E-03	1.42E-04
11		FIRST PREMOLAR	-1.76E-03	7.12E-03	1.95E-04
12		CANINE	-5.08E-03	6.13E-03	-4.23E-04
13		LATERAL INCISOR	-8.68E-03	2.59E-03	-7.14E-04
14		CENTRAL INCISOR	-8.64E-03	1.87E-03	-8.47E-04

Table 3

CLEAR ALIGNER WITH POWER RIDGE ATTACHED
HYDROSTATIC STRESS ON PDL (MPa)

SR NO.	PDL		MINUMUM	MAXIMUM	AVERAGE
1	RIGHT	SECOND MOLAR	-9.65E-04	2.94E-03	1.62E-04
2		FIRST MOLAR	-9.13E-04	1.90E-03	3.89E-05
3		SECOND PREMOLAR	-6.36E-04	1.51E-03	3.51E-05
4		FIRST PREMOLAR	-2.80E-03	1.04E-03	-3.27E-04
5		CANINE	-3.16E-03	1.36E-03	-5.35E-04
6		LATERAL INCISOR	-5.90E-03	1.97E-03	-6.46E-04
7		CENTRAL INCISOR	-6.65E-03	1.60E-03	-8.10E-04
8	LEFT	SECOND MOLAR	-9.15E-04	3.05E-03	1.61E-04
9		FIRST MOLAR	-9.37E-04	1.96E-03	3.78E-05
10		SECOND PREMOLAR	-6.69E-04	1.51E-03	3.52E-05
11		FIRST PREMOLAR	-2.78E-03	9.68E-04	-3.25E-04
12		CANINE	-3.12E-03	1.34E-03	-5.26E-04
13		LATERAL INCISOR	-6.10E-03	1.96E-03	-6.49E-04
14		CENTRAL INCISOR	-6.56E-03	1.61E-03	-8.26E-04

Table 4

CONVENTIONAL BRACKETS WITH MINISCREW AND ECHAIN
HYDROSTATIC STRESS ON PDL (MPa)

SR NO.	PDL		MINUMUM	MAXIMUM	AVERAGE
1	RIGHT	SECOND MOLAR	-4.58E-03	1.09E-02	6.48E-04
2		FIRST MOLAR	-3.18E-03	7.64E-03	2.66E-04
3		SECOND PREMOLAR	-3.55E-03	7.40E-03	6.99E-04
4		FIRST PREMOLAR	-8.20E-03	3.43E-02	9.15E-04
5		CANINE	-2.29E-02	2.89E-02	-2.36E-03
6		LATERAL INCISOR	-4.20E-02	1.23E-02	-3.38E-03
7		CENTRAL INCISOR	-4.74E-02	1.03E-02	-4.47E-03
8	LEFT	SECOND MOLAR	-4.36E-03	1.15E-02	6.41E-04
9		FIRST MOLAR	-3.32E-03	7.99E-03	2.68E-04
10		SECOND PREMOLAR	-3.54E-03	7.37E-03	7.14E-04
11		FIRST PREMOLAR	-8.54E-03	3.44E-02	9.43E-04
12		CANINE	-2.36E-02	2.95E-02	-2.34E-03
13		LATERAL INCISOR	-4.36E-02	1.26E-02	-3.37E-03
14		CENTRAL INCISOR	-4.68E-02	1.03E-02	-4.52E-03

Table 5

CLEAR ALIGNER WITH MINISCREW AND ECHAIN HYDROSTATIC STRESS ON PDL (MPa)					
SR NO.	PDL		MINUMUM	MAXIMUM	AVERAGE
1	RIGHT	SECOND MOLAR	-6.83E-03	1.98E-02	1.07E-03
2		FIRST MOLAR	-6.85E-03	1.38E-02	3.03E-04
3		SECOND PREMOLAR	-4.64E-03	1.23E-02	5.11E-04
4		FIRST PREMOLAR	-1.54E-02	7.26E-03	-1.66E-03
5		CANINE	-2.08E-02	1.05E-02	-3.46E-03
6		LATERAL INCISOR	-4.51E-02	1.67E-02	-4.88E-03
7		CENTRAL INCISOR	-5.13E-02	1.27E-02	-6.35E-03
8	LEFT	SECOND MOLAR	-6.51E-03	2.06E-02	1.05E-03
9		FIRST MOLAR	-7.03E-03	1.43E-02	3.02E-04
10		SECOND PREMOLAR	-4.61E-03	1.24E-02	4.92E-04
11		FIRST PREMOLAR	-1.51E-02	7.30E-03	-1.64E-03
12		CANINE	-2.11E-02	1.05E-02	-3.45E-03
13		LATERAL INCISOR	-4.65E-02	1.67E-02	-4.89E-03
14		CENTRAL INCISOR	-4.99E-02	1.27E-02	-6.47E-03

Table 6

Negative values below **-0.0047 MPa/ -4.7x10^{-3} (i.e., compressive pressures above 0.0047 MPa)** pose a considerably higher external root resorption risk.

MODEL 1:

In this model, the least amount of PDL hydrostatic pressure was seen in the central incisors -0.00869 MPa (maximum PDL stress: 0.00187/ 1.87x10^{-3} MPa). The maximum amount of PDL hydrostatic pressure was seen in canines 0.00599/ 5.99x10^{-3} MPa (minimum PDL stress: -0.00496/ -4.96x10^{-3} MPa). The average PDL hydrostatic pressure/ von misses stress placed on the anterior segment was -0.000658/ -6.58x10^{-4} MPa (Figures 1, 5 and Table 3).

MODEL 2:

In this model, the least amount of PDL hydrostatic pressure was seen in the central incisors -0.00665 MPa (maximum PDL stress: 0.0016/ 1.6x10^{-3} MPa). The maximum amount of PDL hydrostatic pressure was seen in lateral incisors 0.00197/ 1.97x10^{-3} MPa (minimum PDL stress: -0.00590/ -5.90x10^{-3} MPa). The average PDL hydrostatic pressure/ von misses stress placed on the anterior segment was -0.000663/ -6.58x10^{-4} MPa (Figures 2, 6 and Table 4).

MODEL 3:

In this model, the least amount of PDL hydrostatic pressure was seen in the central incisors -0.0474 MPa (maximum PDL stress: 0.00103/ 1.03x10^{-3} MPa). The maximum amount of PDL hydrostatic pressure was seen in canines 0.0289/ 2.89x10^{-2} MPa (minimum PDL stress: -0.0229/ -2.29x10^{-2} MPa). The average PDL hydrostatic pressure/ von misses stress placed on the anterior segment was -0.00341/ -3.41x10^{-3} MPa (Figures 3, 7 and Table 5).

MODEL 4:

In this model, the least amount of PDL hydrostatic pressure was seen in the central incisors -0.0513 MPa (maximum PDL stress: 0.0127/ 1.27x10^{-2} MPa). The maximum amount of PDL hydrostatic pressure was seen in lateral incisors 0.0167/ $1.67x10^{-2}$ MPa (minimum PDL stress: -0.0451/ $-4.51x10^{-2}$ MPa). The average PDL hydrostatic pressure/ von misses stress placed on the anterior segment was -0.00489/ $-4.89x10^{-3}$ MPa (Figures 4, 8 and Table 6).

Model	Least PDL Hydrostatic Pressure (MPa)	Maximum PDL Hydrostatic Pressure (MPa)	Maximum PDL Stress (MPa)	Average PDL Hydrostatic Pressure (MPa)
1	-0.00869	0.00599	0.00187	-0.000658
2	-0.00665	0.00197	0.00160	-0.000663
3	-0.0436	0.0289	0.00103	-0.00341
4	-0.0513	0.0167	0.0127	-0.00489

Table 10.

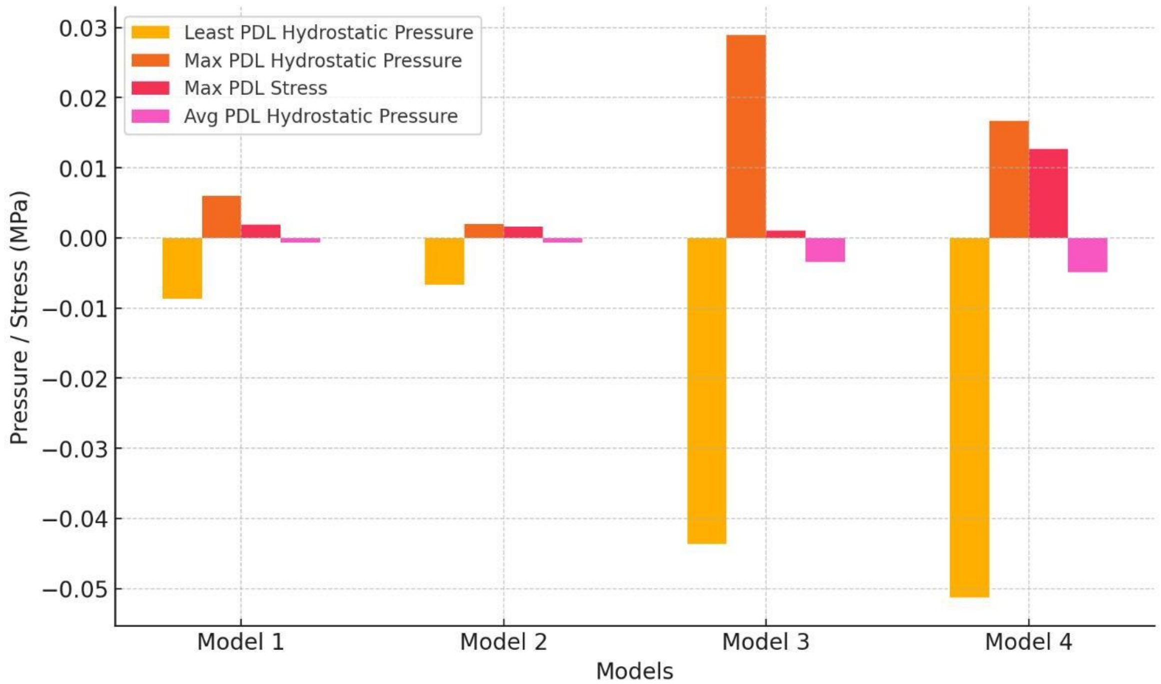


Fig 9. Comparison of PDL hydrostatic pressure and stress across all the models

DISCUSSION

TADs, or temporary anchoring devices, have expanded the options for orthodontic treatment by allowing teeth to move in three dimensions while maintaining bone support.

Whole arch displacement, molar distalization, incisor segment control, and molar control are all areas in which TADs are employed[14]. Additionally, skeletal problems are treated with TADs. People with vertical maxillary excess who have significant alveolar orgival appearance are treated with total arch intrusion[15-16]. It is both practical and beneficial to use miniscrews to reduce gingival appearance and improve gingival smiles, according to recent review research[16].

Using a miniscrew to treat gingival hyperplasia can be done with or without prolonging the periodontal crown. Lower risks, simpler orthodontic biomechanics, reduced patient discomfort, more cost-effectiveness, and the avoidance of alar base broadening are some advantages of this approach over orthognathic surgery[17].

One of the primary causes of TADs is the anterior teeth in gummy smile patients: The deep overbite correction is one of the most difficult orthodontic treatment challenges. In most instances, this correction is caused by extrusion.

The combination of anterior intrusion and posterior teeth in patients with posterior extrusion, which is unfavourable with vertical growth. In these situations, absolute anterior intrusion is required, particularly when there is excessive incisors display.

Various models seen in this study were taken from cases having gummy smile due to excessive incisor display (gumminess in anterior region). Similar FEM study was done with four models for whole maxillary arch intrusion with different positions of TADs, while in this study models were compared only for the anterior segment intrusion where intrusion of posterior segment is not needed.