RESEARCH PAPER

Evaluation Of Stress Distribution Dynamics And Degree Of Difficulty In Traction Of Dilacerated Impacted Canine: A Finite Element Study

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Abstract

Context: Impacted maxillary canines with root dilaceration present significant biomechanical challenges during orthodontic traction due to altered stress distribution.

Aims: To assess the stress distribution and biomechanical difficulty/complexity in terms of variation in degrees of root dilaceration (0-90°) by finite element analysis.

Methods and Material: A 3D finite element model was developed from CBCT data of a maxillary impacted canine. 10 models with dilaceration angles ranging from 0° to 90° were constructed. Vertical orthodontic forces of 60–100 g were applied. Stress distribution (von Mises, principal stress), strain, and total displacement were analysed at the periodontal ligament (PDL), root apex, and cortical bone.

Results: Equivalent stress within the PDL increased as the degree of dilaceration increased, with highest value observed between 50°–70° (~0.002898 MPa), indicating maximum biomechanical resistance. Stress at the root apex was highest at 20° (~0.009876 MPa), suggesting a higher risk of root resorption in mild-to-moderate dilacerations. Cortical bone stress remained relatively constant (~0.00122–0.00129 MPa). Total tooth displacement showed minimal variation across all angles ranging from approximately (~1.10×10^{-4} to 1.23×10^{-4} mm).

Conclusions: Moderate to severe dilacerations makes orthodontic traction more challenging because of increased PDL stress, whereas mild dilacerations are associated with higher apical stress . Root morphology has a major role in influencing biomechanics, with minimal impact on overall tooth displacement.

Keywords: Dilaceration, Impacted canine, Finite element analysis, Orthodontic traction, Stress distribution

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Introduction

Tooth eruption is a complex process influenced by genetic, molecular, and environmental factors, and disturbance in this process may result in tooth impaction.1 A tooth is considered impacted when it fails to erupt into its functional position within the expected time frame. 2.Among impacted teeth, the permanent maxillary canine holds particular clinical significance due to its roles in esthetics, arch stability, and functional occlusion, with a reported prevalence of 1–3%.1,3 Root dilaceration, defined as an abnormal curvature of the crown or root, has a multifactorial etiology that includes trauma, space deficiency, and genetic factors.3 This condition significantly changes the biomechanical behaviour , making orthodontic movement more difficult and increasing the risk of root resorption.4,5 Dilaceration, when associated with impaction complicates orthodontic traction and treatment plans.6

The treatment depends on various factors like age of the patient, degree of root dilaceration, and periodontal status. Options are surgical exposure and subsequent orthodontic traction and extraction and prosthetic replacement.7 However, treatment planning is often based on the clinical judgement because of the lack of adequate biomechanical data. The finite element method (FEM) has become an important technique for analysing stress distribution, strain, and displacement within the tooth–periodontal ligament–bone complex.8

Although several studies has applied the finite element method, the majority have relied on simplified models and rarely considers dilacerated impacted canines which limits their clinical applicability.9 The degree of difficulty in orthodontic traction is influenced by a combination biomechanical, biological, and clinical factors, all of which affect treatment complexity and predictability of tooth movement.10 Impacted canines with dilacerated roots are particularly challenging due to altered stress distribution, increased resorption risk, and reduced orthodontic efficiency.4,5 Despite its clinical importance, this difficulty has rarely been objectively quantified in orthodontic literature. Therefore, this study was design to assess the stress distribution patterns and determine the degree of difficulty in orthodontic traction of impacted maxillary canines with root dilaceration, providing objective data to support better clinical decision-making and improve treatment outcomes.

Material And Methods

This study was approved by Institutional Ethics Committee under the Ethical clearance number: IEC-SGTDCHRI/MDS-ORTHO/2024/33 and was designed as a 3-dimentional FEA to evaluate stress distribution and biomechanical behaviour during orthodontic traction of impacted maxillary canines with varying degrees of root dilaceration. CBCT data of a patient aged 16 years with a favourably impacted maxillary canine with root dilaceration were obtained from the Department of Oral Medicine and Radiology. Ethical approval was obtained before data acquisition. The same CBCT data was exported in Digital Imaging and Communications in Medicine (DICOM) format and imported into Materialise MIMICS (version 18.0) for segmentation and three-dimensional reconstruction. Anatomical structures including the tooth, periodontal ligament (PDL), and surrounding alveolar bone were separated based on density thresholds. The reconstructed model was saved as a stereolithography (STL) file and was transformed into a surface-based CAD model using Geomagic software. The final model was later exported in STEP format and imported into the finite element environment.

Development of Finite Element Models

Ten geometric models of impacted maxillary canines were generated using 3D Experience software, with root dilaceration angles ranging from 0° to 90° in 10° increments [Figure 1]. Each model was incorporated into a maxillary bone framework to simulate realistic anatomical conditions.

Figure 1: 10 Geometric models of impacted maxillary canines with dilacerations (0-90 degrees): generated using 3D Experience software

Meshing and Material Properties

All models were then imported into ANSYS Workbench for finite element analysis. Each model was subdivided into a finite number of elements using an optimized mesh configuration, ensuring computational results.

Material properties were then assigned to the finite element model assuming all components to be homogeneous, isotropic, and linearly elastic in behaviour. The Young's modulus and Poisson's ratio for the tooth, PDL, spongy bone, and cortical bone were defined as :

Tooth: 20300 MPa and 0.26,
PDL: 0.667 and 0.49,
Spongy bone: 13400 MPa and 0.38,
Cortical bone: 34000 MPa and 0.26.

Boundary Conditions and Force Application

The maxillary model was fixed at relevant anatomical boundaries to mimic normal physiological conditions as closely as possible. A vertical orthodontic traction force ranging from 60-100 g was then applied to the crown of the impacted canine in each model, simulating the forces commonly used during clinical orthodontic traction

Outcome Measures

The following biomechanical parameters were assessed:

- Equivalent (von Mises) stress in: Periodontal ligament (PDL), Root apex and Cortical bone.
- Maximum principal stress in: PDL, Root apex and Cortical bone
- Equivalent elastic strain
- Total tooth displacement (deformation)

Data Analysis

Using the different dilaceration angles (0°- 90°) the effect of root curvature on the stress distribution, strain pattern, and overall tooth displacement was compared with the respective results of all ten models. Then the results were interpreted to evaluate the biomechanical difficulty of orthodontic traction with increase in severity of the root dilaceration.

Results

Finite element analysis showed that root dilaceration significantly affected stress distribution within the tooth–periodontal ligament–bone complex, while having minimal influence on overall tooth displacement.

1. Stress Distribution in Periodontal Ligament (PDL)

Equivalent (von Mises) stress in the PDL increased with increasing dilaceration angle. The lowest stress was observed in the non-dilacerated model [Table 1] i.e. 0° followed by a sharp increase at 10°–20°. Peak stress values were observed at [Figure 2] 50°, with similarly high values noted at 60°–70°.

Maximum principal stress (Tensile stress) in the PDL showed a similar pattern, reaching its highest values at 50°–60°. [Table 1]

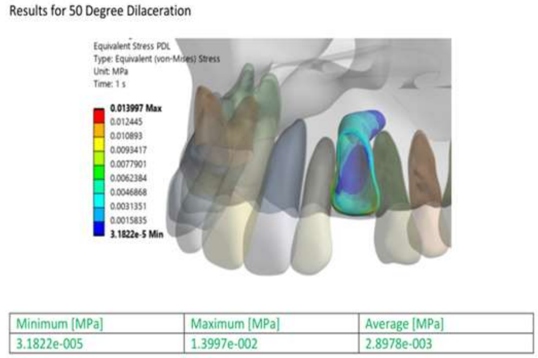

Figure 2: Equivalent stress in PDL on orthodontic traction of canine at 90° dilaceration

2. Stress Distribution at Root Apex

Equivalent stress at the root apex exhibited a different trend. The maximum value was noted at 20° dilaceration [Table 1] after which the stress gradually declined with increasing curvature, reaching the lowest values at severe dilaceration angles (90°). See [Figure 3].

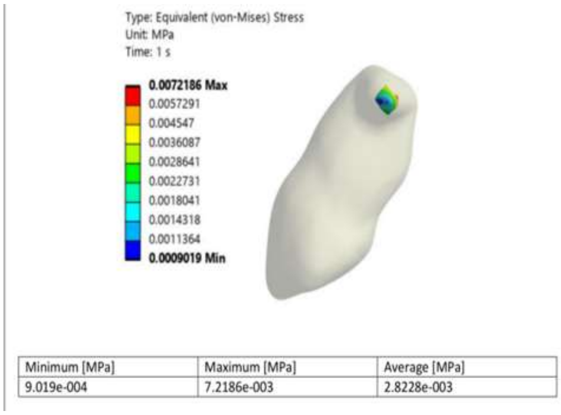

Figure 3: Equivalent stress at root Apex on orthodontic traction of canine at 90° dilaceration

Maximum principal stress at the apex showed a similar pattern, with higher values in mild to moderate dilacerations (10°–30°) and decreased stress at higher angles.

3. Stress Distribution in Cortical Bone

Equivalent and Principal stress in cortical bone remained relatively stable across all models. See [Table 1]

4. Equivalent Elastic Strain

Equivalent elastic strain in PDL showed a slight increase with increasing dilaceration angle, suggesting greater tissue deformation at higher curvatures. See [Figure 4].

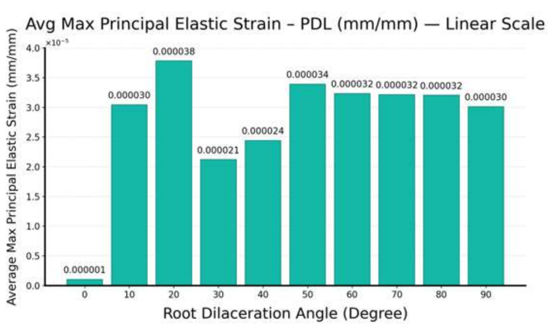

Figure 4: Variation of Elastic Strain in PDL with increasing dilaceration angles

5. Total Tooth Displacement

Total tooth displacement remained fairly uniform among all models [Table 1]. The highest displacement was noted in non-dilacerated model (0°), with only minor variations as the dilaceration increased. See [Table 1] showing least tooth displacement at 90° dilaceration.

Table 1: Data Points Recorded at Various Root Curvature Standard Increments

Overall Findings [Table 1.0]

- PDL stress increased with dilaceration, peak values were at 50°–70°
- Root apex stress was highest at 20°
- Cortical bone stress remained stable
- Strain increased slightly with curvature.
- Tooth displacement remained largely uniform throughout.

Parameter	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
PDL Equiv Stress (MPa)	0.000084	0.002647	0.002526	0.001843	0.002132	0.002898	0.002763	0.002841	0.002764	0.002567
Apex Equiv Stress (MPa)	0.006164	0.007035	0.009876	0.003693	0.006811	0.003565	0.005193	0.003980	0.003289	0.002823
Cortical Equiv Stress (MPa)	0.001224	0.001259	0.001261	0.001279	0.001281	0.001289	0.001266	0.001271	0.001270	0.001248
PDL Max Principal Stress (MPa)	0.000074	0.000942	0.000790	0.000704	0.000754	0.001369	0.001304	0.000863	0.001195	0.001270
Apex Max Principal Stress (MPa)	0.003977	0.004824	0.008523	0.005029	0.005645	0.005711	0.006146	0.004961	0.003891	0.002566
Cortical Max Principal Stress (MPa)	0.000801	0.000834	0.000837	0.000843	0.000846	0.000852	0.000839	0.000842	0.000842	0.000830
PDL Max Principal Elastic Strain (MPa)	0.000001	0.000030	0.000038	0.000021	0.000024	0.000034	0.000032	0.000032	0.000032	0.000030
Tooth Total Deform (mm)	1.235e-04	1.123e-04	1.114e-04	1.139e-04	1.170e-04	1.192e-04	1.189e-04	1.198e-04	1.204e-04	1.103e-04

Discussion:

In this finite element study, the biomechanics of impacted maxillary canine with different root dilacerations were analysed, considering stress distribution, principal stress, elastic strain, and tooth displacement within the periodontal ligament (PDL), root apex, and cortical bone. The findings showed that with increase in root dilaceration, the stress distribution patterns were affected during orthodontic traction, thereby increasing the biomechanical difficulty. The PDL showed maximum biomechanical changes with increase in root dilaceration. Similarly, the equivalent and principal stresses showed a significant increase between moderate and severe dilaceration angles (50°–70°), indicating the increased resistance to orthodontic tooth movement due to change in the force vectors as well as increased bending forces of the ligament. In case of Equivalent Stress in PDL, when orthodontic traction is applied to a dilacerated tooth, the force no longer acts along the long axis of the root but instead generates bending and shears forces within the periodontal ligament. Similar observations were reported by Tanne et al.11 and Cattaneo et al.12, who demonstrated that irregular root morphology produces non-uniform periodontal stress distribution. Increased tensile stress and elastic strain observed in the present study also support the findings of Toms and Eberhardt13 and Qian et al.14, suggesting that root curvature increases biomechanical resistance during orthodontic traction. Excessive tensile stress may contribute to periodontal tissue damage or delayed tooth movement. The higher principal stress values seen in moderate to severe dilaceration indicate the need for better orthodontic control and the use of lighter forces during the traction of severely dilacerated canines.

The present study showed that the maximum equivalent stress at root apex was observed at moderate dilacerations, around 20°, after which the stress values gradually decreased with increasing angulations. This finding indicated that mild to moderate dilaceration leads to greater stress concentration at the root apex, as the orthodontic force vector is directed more closely through the apical region, causing localised stress buildup. Similar findings were reported by D. J. Rudolph et al.15, who demonstrated that orthodontic force direction significantly influences apical stress concentration and root resorption risk. Likewise, Krishnan and Davidovitch16 reported that excessive apical stress may initiate external apical root resorption during orthodontic treatment. Maximum principal stress at the root apex also showed peak values at 20° dilaceration, followed by gradual reduction with increasing curvature. This may be explained by changes in the effective line of force action caused by root dilaceration. In cases of moderate dilaceration, stress tends to remain concentrated around the root apex, whereas in severe dilacerations, it redistributes along the curved root surface extending from the site of dilaceration toward the apex. Nevertheless, unfavourable clinical outcomes are thought to be more closely associated with hydrostatic pressure and biological responses rather than principal stress values alone.

This study showed that equivalent stress within the cortical bone remained relatively stable across all dilaceration angles, suggesting that the alveolar bone is capable of distributing orthodontic forces effectively regardless of the root curvature. Similar findings were reported by Natali et al.17, who demonstrated efficient load-bearing and stress dissipation within alveolar bone during orthodontic loading. Likewise, Qian Yang3 observed that cortical bone stresses are less sensitive to traction variations than PDL and root stresses. Maximum principal stress in cortical bone also remained within a narrow range, suggesting maintained biomechanical stability regardless of root angulation. However as reported by Phetcharat Dhammayannarangsi18, cortical bone stress values are affected by the material properties of PDL and should therefore be considered comparative estimates within the model rather than absolute indicators of clinical risk. Overall, the findings suggest that biomechanical difficulty in dilacerated canines is primarily associated with periodontal ligament and apical stress distribution rather than cortical bone response.

Total tooth displacement showed slight variation across different dilaceration angles, suggesting that root curvature mainly alters internal stress distribution rather than overall tooth movement. Similar findings were reported by Cattaneo et al.12 and Toms and Eberhardt.13 Likewise, Bishara19 reported that traction difficulty depends more on force direction and tooth position than root morphology alone. Although Becker and Chaushu20 noted greater difficulty in severely dilacerated teeth, the present findings suggest that orthodontic traction can still be performed when appropriate biomechanics are applied.

Clinical Implication

The findings suggest some clinical implications that an orthodontist should implement during traction of dilacerated impacted canine:

- Light and controlled forces,
- Perform care CBCT based assessment of root morphology before treatment,
- Closely monitor for root resorption throughout the treatment.

Limitations

This study has few limitations. First, the FEM model treated the material properties as if they were uniform and isotropic, whereas biological tissues exhibit anisotropic characteristics. Also, while we simulated static orthodontic forces, it’s important to remember that tooth movement typically occurs under dynamic biological processes that change over time. In addition, individual patient differences, such as variation in bone density, periodontal health, and root morphology were not incorporated into the model which could affect the outcomes.

Conclusion:

Root dilaceration of impacted maxillary canines presents interesting biomechanical challenges for orthodontic traction but understanding these challenges can lead to effective solutions. As the severity of root dilaceration increases, there is a significant impact on the stress distribution in periodontal ligament especially in moderate to severe angulations which makes the traction more complex. Furthermore, it was the mild to moderate dilaceration cases that showed the highest stress at the root apex, not the severe ones. That is something worth paying attention to because elevated apical stress is directly linked to root resorption risk, which nobody wants to see happen mid treatment. The severe dilacerations had lower apical stress readings, which might seem surprising at first.

As for the cortical bone stress, it stayed fairly consistent regardless of how severe the dilaceration angle was. This tells us that the difficulties are not really coming from the surrounding bone but rather from how altered root shape interacts with the periodontal ligament under traction forces. While total tooth displacement is roughly comparable across all groups, though teeth without any dilaceration tended to show slightly more movement overall compared to the dilacerated ones.

The result points clearly the importance of moderation in force application when treating impacted dilacerated canines. Light continuous force along with deliberate biomechanical planning and attentive follow up appear to be what separates good outcomes from complicated ones. What remains less well understood is how dynamic force system interacts with the anatomical variations seen across patients. Future work that builds these factors into study design would meaningfully strengthens both the simulation models and the clinical conclusion drawn from them.

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