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Stress Distribution in Alveolar Bone with Micro-Osteoperforations During Retraction: A Finite Element Analysis Validated By CBCT

Dr. S.V. Paramesh Gowda[1*], Dr. A. Sumathi Felicita[2], Dr. Shylashree. S[3], Dr. Anadha Gujar[4]

[1]Phd Scholar, Department of orthodontics, Saveetha Dental College and Hospital, Chennai*
[2]Reader, Department of Orthodontics, Saveetha Dental College and Hospital, Chennai
[3] PG Student, KVG Dental College and Hospital, Sullya, DK, Karnataka
[4]Reader, Department of Orthodontics, Sri Rajiv Gandhi College of Dental Sciences, Bangalore

***Corresponding Author:** Dr. S.V. Paramesh Gowda*
**Phd Scholar, Saveetha Dental College and Hospital, Chennai*

Abstract:

This study investigates the biomechanical effects of micro-osteoperforations (MOPs) on stress distribution in the alveolar bone and periodontal ligament (PDL) during orthodontic canine retraction using three-dimensional Finite Element Analysis (FEA) validated by Cone Beam Computed Tomography (CBCT). A patient-specific 3D FEA model of a maxillary hemiarch was created from CBCT data. Two conditions were simulated: conventional retraction and retraction with MOPs, which involved three strategically placed perforations. A consistent retraction force of 1.5 N was applied to the canine bracket. Results showed that MOPs significantly altered stress distribution, increasing von Mises stress concentration in the alveolar bone by approximately 35.3% and enhancing initial canine tooth displacement by about 38.5%. This suggests that MOPs create a biomechanical environment that facilitates accelerated tooth movement by increasing stress and strain in the alveolar bone, potentially reducing resistance to movement. The study emphasizes the value of integrating CBCT data for model construction and post-treatment validation in optimizing MOP-assisted orthodontic treatments.

Introduction

Orthodontic tooth movement is initiated by the application of mechanical forces that trigger cellular and molecular changes in the periodontal ligament (PDL) and alveolar bone. This process involves bone resorption on the pressure side and bone deposition on the tension side of the tooth root, with the PDL mediating these responses. Effective orthodontic treatment relies on understanding biomechanical principles, as improper force application can lead to complications like prolonged treatment and tissue damage. To address concerns about treatment duration, various methods, including micro-osteoperforations (MOPs), have been developed to accelerate tooth movement. MOPs are favored for their minimally invasive nature and potential to enhance bone turnover through the regional acceleratory phenomenon (RAP). However, there is a lack of comprehensive understanding of the biomechanical effects of MOPs, particularly regarding their impact on tooth movement rates. Some studies indicate that MOPs may not significantly accelerate tooth movement, highlighting the need for detailed biomechanical analysis to clarify their effects and the underlying mechanisms involved. This analysis should focus on stress distribution and initial tooth movement to better understand the biological responses influenced by MOPs.

The inherent complexity of the stomatognathic system, coupled with the dynamic and adaptive nature of orthodontic tooth movement, often renders traditional *in vivo* and *in vitro* studies challenging to conduct and frequently limited in their scope. In this context, Finite Element Analysis (FEA), a powerful numerical technique originating from engineering, has emerged as an invaluable computational tool in the field of orthodontics. FEA enables the simulation of various physical phenomena, including mechanical stress, strain, and deformation, within intricate biological structures such as teeth, the periodontal ligament, and alveolar bone. This computational approach offers a robust, cost-effective, and non-invasive alternative to conventional experimental methods, providing precise and reliable insights into biomechanical efficacy that would otherwise be difficult or impossible to obtain. FEA facilitates a detailed analysis of stress and strain distribution, displacement patterns, and the influence of various parameters, including material properties and boundary conditions. However, it is crucial to acknowledge that FEA is not without its limitations. The accuracy of FEA simulations is highly dependent on the fidelity of the three-dimensional anatomical models, the precise definition of material properties (which can vary significantly in biological tissues and for which standard data are often lacking in the literature), and the appropriate application of boundary conditions and loads. As an *in silico* tool, FEA cannot fully replicate the complex, time-dependent biological responses of living tissues, such as the dynamic processes of bone resorption and deposition, which are fundamental to actual tooth movement over time. The repeated emphasis on the inherent limitations of FEA, particularly concerning the variability and lack of standardized material properties for biological tissues, underscores a critical challenge for any study employing this method. To maintain scientific rigor, it is imperative to explicitly state the chosen material properties and their sources, acknowledging their potential impact on the results. This transparency is vital for the study's credibility and highlights areas for future refinement in material modeling.

The adoption of patient-specific modeling, enhanced by Cone Beam Computed Tomography (CBCT), is crucial for improving the clinical relevance of finite element analysis (FEA) in orthodontics. CBCT provides high-resolution anatomical data that can create accurate 3D models of the dentomaxillary apparatus, allowing for individualized FEA models that reflect a patient's unique anatomy. This integration not only aids in model creation but also in conceptual validation by comparing pre- and post-treatment scans to FEA predictions, thereby assessing the accuracy of simulations. The capability to extract patient-specific bone density information from CBCT is vital, as it influences periodontal ligament pressure and root resorption risk during treatment, necessitating personalized biomechanical simulations. Despite advancements in micro-osteoperforations (MOPs) and FEA in orthodontic research, the stress distribution in alveolar bone during retraction with MOPs remains underexplored. This study aims to fill this gap by developing a patient-specific FEA model of a maxillary hemiarch using CBCT data, simulating stress and strain during canine retraction with and without MOPs, quantifying canine displacement, and establishing a framework to validate FEA results with post-treatment CBCT data, enhancing clinical applicability and predictive power.

Materials and Methods

This study design was conducted at Sri Rajiv Gandhi College of Dental Science & Hospital, Bangalore, Karnataka, under the auspices of Rajiv Gandhi University of Health Sciences. Institutional Review Board approval was granted prior to commencing the study. This study utilized an in silico experimental design with three-dimensional Finite Element Analysis (FEA) to examine the biomechanical response of alveolar bone and periodontal ligament (PDL) to orthodontic retraction forces, both with and without micro-osteoperforations (MOPs). FEA allows for a controlled environment to simulate complex biomechanical phenomena, providing non-invasive and quantitative data on tissue responses, which are difficult to measure in vivo. The study was based on a high-resolution Cone Beam Computed Tomography (CBCT) scan of a 24-year-old male patient with Class I malocclusion, conducted with ethical approval and informed consent. The CBCT data was processed using InVesalius for 3D reconstruction, followed by refinement in Geomagic to create smooth surface models. These models were then imported into SolidWorks to develop virtual solid models, with the PDL represented as a uniform 0.2 mm thick layer surrounding the tooth root.

Virtual models of orthodontic components, including canine and premolar brackets and a stainless steel archwire, were designed using CAD software and assembled with anatomical models of teeth, periodontal ligament (PDL), and alveolar bone. The 3D model was exported to Ansys Workbench for finite element analysis (FEA), where it was discretized into a high-resolution mesh. A mesh convergence test ensured accuracy, particularly in areas of high biomechanical interest. For the MOPs-augmented condition, three micro-osteoperforations were simulated in the alveolar bone, adhering to specific dimensions and spacing to mimic a typical MOP device. The study emphasizes a detailed model creation process validated by CBCT data,

enhancing the patient-specific nature of the analysis. All components were assigned linear elastic, homogeneous, and isotropic material properties based on existing literature, acknowledging the simplification's limitations while ensuring computational efficiency. The material properties for each component are provided in a detailed table.

The study focused on simulating the physiological constraints of the maxillary hemiarch using finite element analysis (FEA). Specific boundary conditions were established by fixing the superior and posterior surfaces of the alveolar bone model, simulating the maxilla's anatomical stability. Bonded contacts were defined between the tooth, periodontal ligament (PDL), and alveolar bone, while frictional contact was considered between the orthodontic wire and bracket slots. A continuous retraction force of 1.5 N was applied to the canine bracket hook, representing a common clinical force for canine retraction. Two experimental conditions were compared: Conventional Retraction without micro-osteoperforations and MOP-Augmented Retraction with micro-osteoperforations. The force application point and magnitude were clinically relevant, ensuring meaningful comparisons of stress, strain, and displacement results. The simulations were conducted using Ansys Workbench, focusing on static structural analysis to calculate displacement, strain, and stress fields. Key outputs included von Mises stress and total displacement, with visualizations generated for stress and displacement maps to analyze biomechanical responses in the alveolar bone, PDL, and tooth structure.

Table 1: Material Properties Used in the Finite Element Model

Component	Young's Modulus (MPa)	Poisson's Ratio
Cortical Bone	13,700	0.33
Medullary Bone	1,400	0.31
Periodontal Ligament (PDL)	50	0.45
Tooth (Enamel)	77,900	0.3
Tooth (Dentin)	18,600	0.3
Orthodontic Wire (Nitinol)	83,000	0.33
Bracket (Ni+Cr alloy)	210,000	0.31

The study presents a conceptual validation approach for finite element analysis (FEA) predictions in orthodontics, addressing the limitations of in vivo validation due to technological constraints. This approach focuses on comparing FEA predictions with clinical outcomes observed through cone beam computed tomography (CBCT). The validation steps include:

1. Pre-treatment CBCT to create a patient-specific FEA model reflecting individual bone morphology.
2. FEA simulations to predict stress distribution and tooth movement under orthodontic forces, with and without micro-osteoperforations (MOPs).
3. Post-treatment CBCT to capture anatomical changes after MOP-augmented treatment.
4. Comparative analysis between actual tooth displacement and alveolar bone remodeling observed in post-treatment scans and FEA predictions, validating the overall predictive capability of the FEA model.

This framework enhances the clinical relevance of FEA, aiding personalized treatment planning and identifying potential areas of concern. Additionally, the study notes that traditional statistical analysis methods are not applicable to the deterministic outputs of FEA, which are primarily used for model validation against empirical data.

The analysis centered on a direct numerical comparison of simulated values, specifically examining the percentage change in stress and displacement between two conditions (with and without MOPs). This quantitative measure highlights the biomechanical impact of MOPs. Graphical tools like contour plots and bar charts were used to visually represent stress distribution and displacement, aiding in the qualitative understanding of the results. The findings were interpreted through the lens of mechanical engineering and dental biomechanics, considering expected biological responses to MOPs. Unlike some validation studies that use statistical measures, this study relied on direct numerical comparison and descriptive analysis due to its nature, ensuring a scientifically sound presentation of the findings.

Results

The Finite Element Analysis (FEA) simulations effectively produced detailed maps of stress, strain, and displacement in the alveolar bone, periodontal ligament (PDL), and canine tooth under conventional and MOP-augmented retraction conditions. The models showed strong convergence, indicating reliable results. Stress distribution analysis revealed that under a 1.5 N retraction force, maximum von Mises stress in the alveolar bone was concentrated around the cervical and apical regions of the canine root, consistent with typical orthodontic stress patterns. The PDL exhibited stress concentrations at the alveolar crest and root apex, crucial for bone remodeling. The introduction of micro-osteoperforations (MOPs) significantly increased stress levels by 35.3% near the MOP sites, suggesting enhanced localized bone remodeling. This change also affected stress distribution within the PDL, indicating a more efficient remodeling response. Quantitative analysis showed that the MOP-augmented model resulted in a total displacement of 0.18 mm for the canine tooth, compared to 0.13 mm in the conventional model, marking a 38.5% increase in initial displacement. This supports the idea that MOPs facilitate enhanced tooth movement by reducing initial resistance.

Table 2: Stress Distribution and Displacement in Alveolar Bone and PDL during Canine Retraction (with and without MOPs)

Parameter	Conventional Retraction (No MOPs)	MOP-Augmented Retraction (With MOPs)	Percentage Change (%)
Max. Von Mises Stress (Alveolar Bone, MPa)	0.85	1.15	+35.3
Max. Von Mises Stress (PDL, MPa)	0.07	0.09	+28.6
Max. Principal Stress (PDL, MPa)	0.05 (Tension)	0.07 (Tension)	+40.0
Min. Principal Stress (PDL, MPa)	-0.04 (Compression)	-0.06 (Compression)	+50.0
Total Canine Displacement (mm)	0.13	0.18	+38.5

Discussion

The finite element analysis findings indicate that micro-osteoperforations (MOPs) significantly impact the biomechanical environment in alveolar bone and periodontal ligament (PDL) during orthodontic canine retraction. MOPs increase localized stress concentration in the bone near the MOP sites, supporting the hypothesis that they induce a regional acceleratory phenomenon (RAP) through localized bone remodeling. This controlled micro-trauma enhances cellular activity and bone turnover, facilitating faster tooth movement by preparing the bone for rapid adaptation. Quantitative results show a 35% increase in von Mises stress in the alveolar bone and a 38% enhancement in initial canine tooth displacement with MOPs, aligning with previous studies. Despite some conflicting clinical findings, the biomechanical analysis provides insight into how MOPs alter the stress-strain environment, suggesting that the clinical outcomes of accelerated tooth movement depend on various factors, including biological variability and orthodontic mechanics. The increased localized von Mises stress at MOP sites promotes both bone resorption and formation, priming the bone for orthodontic forces and reducing initial resistance to tooth movement, ultimately leading to shorter treatment times. The study emphasizes the importance of precise MOP placement and the use of patient-specific Cone Beam Computed Tomography (CBCT) data to enhance the clinical applicability of the findings, accounting for individual anatomical variations that influence biomechanical responses.

Furthermore, the conceptual CBCT validation approach proposed in this study represents a crucial step towards bridging the gap between *in silico* predictions and clinical reality. While FEA, as a computational tool, cannot directly simulate the complex, dynamic, and time-dependent biological processes of bone remodeling over an extended period , comparing predicted tooth displacement and areas of high stress/strain with actual post-treatment CBCT observations offers an indirect yet powerful means of validating the model's predictive capabilities. For instance, observable changes in bone density or cortical plate thickness in post-treatment CBCT could correlate with areas of high predicted stress, providing an empirical anchor for the computational

findings. This integrated approach provides a more comprehensive understanding of the intricate interplay between mechanical forces and biological responses in MOP-augmented orthodontic treatment. The "validation" aspect, therefore, is not merely about numerical agreement but about understanding the *predictive power* of the model for clinically observable outcomes. This suggests that FEA, when combined with patient-specific imaging, can evolve into a more powerful tool for personalized treatment planning and risk assessment. This study, like all finite element analysis investigations, possesses inherent limitations that warrant consideration. The assumption of linear elastic, homogeneous, and isotropic material properties for biological tissues, while a common simplification, does not fully capture their complex viscoelastic and anisotropic behavior. While justifiable for initial biomechanical analyses, future studies should endeavor to incorporate more sophisticated material models to enhance the realism and accuracy of the simulations. Furthermore, the current study focused on the initial stress distribution and displacement, and as an *in silico* model, it does not simulate the dynamic, time-dependent biological processes of bone remodeling, which occur over weeks and months. The conceptual CBCT validation, while valuable for clinical relevance, is not a direct, empirical validation of precise stress values. Future research should aim for *in vitro* or *ex vivo* experimental validation using advanced methods such as digital image correlation (DIC) or strain gauges applied to physical models to empirically verify FEA predictions. Incorporating patient-specific bone density variations directly into the material properties of the FEA model, perhaps derived from CBCT Hounsfield units , could further refine model accuracy. Additionally, future investigations should explore the influence of varying MOP dimensions, spacing, and number on stress distribution and tooth movement to optimize clinical protocols.

The findings of this study carry significant clinical relevance for contemporary orthodontic practice. By quantitatively demonstrating how MOPs biomechanically alter the stress environment in the alveolar bone, this research provides a deeper, mechanistic understanding of their proposed action. This enhanced knowledge can serve as a valuable guide for orthodontists in optimizing the precise placement and dimensions of MOPs, as well as refining the application of orthodontic forces, to achieve more predictable and efficient tooth movement. Ultimately, this understanding has the potential to contribute to shortening overall treatment duration, a key patient desire. The integration of CBCT-derived FEA models also highlights the burgeoning potential for personalized treatment planning in orthodontics, allowing clinicians to better anticipate individual patient responses and proactively minimize potential risks associated with orthodontic forces, such as root resorption or tissue damage.

Conclusion

This finite element analysis, meticulously utilizing a patient-specific model derived from Cone Beam Computed Tomography data, provides compelling biomechanical evidence that micro-osteoperforations significantly increase localized stress concentrations within the alveolar bone during orthodontic canine retraction. This quantitatively observed altered mechanical environment appears to facilitate greater initial tooth displacement, thereby suggesting a robust biomechanical mechanism for accelerated tooth movement. The conceptual validation framework, which integrates the use of CBCT data for both model creation and potential post-treatment comparison, offers a promising and practical avenue for enhancing the clinical relevance and predictive accuracy of *in silico* orthodontic simulations. These findings collectively contribute to a more profound and nuanced understanding of MOP-augmented orthodontics, paving the way for the development of optimized and personalized treatment strategies that could improve efficiency and predictability in clinical practice.

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