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Original Article

Impact of First Maxillary Molar Abutment Inclination on Stress Distribution in Two Types of Zirconia Crowns: A 3D Finite Element Analysis

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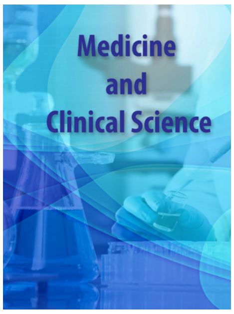

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Keywords

Zirconia crowns, finite element analysis, stress distribution, abutment inclination, occlusal loading, dental prosthetics

Abbreviations

2D: Two-dimension; 3D: Three-dimension; CAD/CAM: Computer-aided design/ Computer-aided manufacturing program; FEA: Finite Element Analysis; FEM: Finite Element Methods; MPa: Megapascal; N: Newton's Force unit; PFM: Porcelain Fused to Metal; RME: Rapid maxillary expansion; TMJ: Temporal-mandibular joint; UPCB: Unilateral Posterior Crossbite; Y-TZP : Yttria-Stabilized Tetragonal Zirconia Polycrystals.

Abstract

Background: *This study aimed to evaluate the impact of abutment inclination on stress distribution in monolithic and bi-layered zirconia crowns for maxillary first molars, using three-dimensional finite element analysis (FEA).*

Methods: *Three-dimensional models of maxillary and mandibular first molars were developed from micro-computed tomography data, incorporating detailed anatomical and material properties. Six FEA models were created to simulate three occlusal conditions: centric occlusion, palatal crossbite, and buccal crossbite. A static load of 200 N was applied in vertical, oblique, and horizontal directions to replicate physiological masticatory forces.*

Results: *The analysis revealed marked differences in von Mises stress distribution and magnitude across crown types and abutment inclinations. Stress concentrations were notably higher under oblique and horizontal loads, especially in crossbite conditions. Monolithic zirconia crowns exhibited more uniform and favorable distribution than bi-layered crowns across all scenarios.*

Conclusions: *The findings suggest that abutment inclination and crown type significantly influence stress behavior in zirconia restorations. Monolithic zirconia crowns are preferable for managing stress, particularly in non-ideal occlusal situations, and may contribute to enhanced durability and clinical performance.*

Introduction

In the late 20th century, the emergence of zirconia as a novel ceramic material transformed restorative dentistry, driven by increasing demands for esthetics and growing concerns over the biocompatibility of metal alloys. All-ceramic crown systems are designed to replicate the natural optical properties of teeth, and among these, materials such as leucite-reinforced and lithium disilicate glass ceramics, as well as oxide ceramics like alumina and zirconia, have demonstrated promising performance for both anterior and posterior restorations [1].

Despite advancements, the long-term survival rates of all-ceramic restorations—particularly bi-layered and monolithic zirconia crowns—have been reported to be lower than those of conventional porcelain-fused-to-metal (PFM) crowns (Pjetursson et al., 2007) [2]. A major challenge lies in the mechanical failures of ceramic restorations, including chipping and delamination of veneering layers. With the increasing use of CAD/CAM technology in fabricating zirconia crowns, attention has shifted toward optimizing clinical protocols, such as abutment height and axial angulation, to achieve favorable stress distribution across the crown, cement, and underlying tooth structure—factors known to impact restoration longevity [3].

Human occlusion, while varying individually, follows a broadly consistent distribution pattern across populations [4]. Normal occlusion, as defined by Angle, is characterized by the mesiobuccal cusp of the maxillary first molar occluding with the buccal groove of the mandibular first molar, creating a harmonious occlusal curve [5]. Malocclusions, such as unilateral posterior crossbite, affect approximately 12% of the population [6]. In cases like unilateral posterior single molar buccal crossbite, the mandibular buccal cusps occlude palatal to the palatal cusps of the maxillary molar, leading to non-ideal loading conditions [7].

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To investigate how these occlusal variations influence restoration performance, various analytical techniques have been employed, with experimental methods and finite element analysis (FEA) being particularly effective in evaluating stress distribution in restored teeth [8]. In prosthodontic treatment of inclined abutment teeth, conventional approaches—such as orthodontic correction or endodontic therapy—may be impractical due to discomfort, cost, and time constraints [9].

Given these considerations, the present FEA study aimed to assess how different occlusal conditions and zirconia crown types affect stress distribution in the maxillary first molar. The null hypothesis proposed that neither occlusal variation nor crown type would significantly influence von Mises stress distribution within the restorative system.

Materials and Methods

A 3D model of a maxillary and mandibular first molar was constructed based on Micro-Computed Tomography Scanning of a patient with complete dentition and fully erupted left mandibular and maxillary first molars in semi-maximum intercuspation. This was carried out in an interactive medical image processing software (Mimics 19.0; Materialise, Leuven, Belgium). The internal volume of the 3D model was then constructed by adding cortical bone, cancellous bone, periodontal ligament, pulp, dentine, enamel, and restorative components [10].

An anatomically correct 3D prototype of a maxillary first molar full crown preparation was modeled by reducing proximal walls by 1.5 mm with a chamfer finish line and the occlusal surface by 2.0 mm using CAD software (Solidworks; Luxology, LLC) to receive a monolithic zirconia crown or bi-layered zirconia crown and a 100-µm-thick cement layer (zinc-oxide phosphate cement) [11] (Figure 1).

The crowns and abutments were estimated to have bonded uniformly and perfectly in silico via Solidworks and were further imported into ANSYS software (ANSYS 18.1; ANSYS Inc., Canonsburg, PA, USA) for mesh generation. After a convergence analysis, the mesh elements were created as first-order tetrahedral linear elements. Models of the monolithic zirconia crown and bi-layered zirconia crown with the surrounding structures included 372,930 nodes and 235,320 elements, and 383,513 nodes and 239,930 elements, respectively (Figure 2).

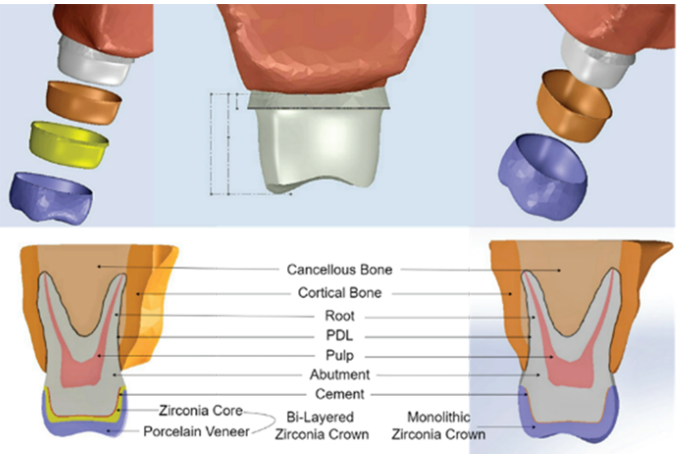

Figure 1. *Schematic illustration of three-dimensional geometric models.*

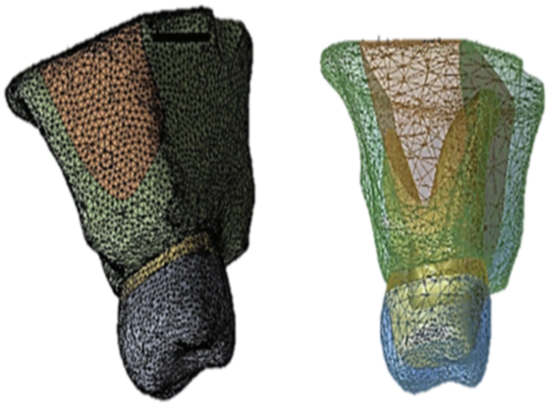

Figure 2. *Tetrahedral mesh structure of a three-dimensional finite element model.*

Six 3D FEA models were studied and divided into two groups (n = 3/group):

Group #1: Monolithic zirconia crown of maxillary 1st molar in centric occlusion Model (a), palatal crossbite malocclusion Model (b), and buccal crossbite malocclusion Model (c) to the mandibular 1st molar.

Group #2: Bi-layered zirconia crown of maxillary 1st molar in centric occlusion Model (d), palatal crossbite malocclusion Model (e), and buccal crossbite malocclusion Model (f) to the mandibular 1st molar.

All mechanical properties of the model components were assumed to be homogeneous, linearly elastic, and isotropic.

A static load of 200 N in vertical (0°), oblique (45°), and horizontal (90°) directions was applied to the study models during the maximum intercuspation phase to simulate physiologic masticatory forces and external traumatic forces, respectively [12].

The upper molar models and the lower tooth crown were aligned in occlusion, referencing specific points corresponding to various occlusion types examined in this study, as detailed in the corresponding paragraphs (Figures 3A–C). To ensure stability, displacement and rotation constraints were imposed on each node situated at the outermost part of the cortical bone supporting the restored tooth [13].

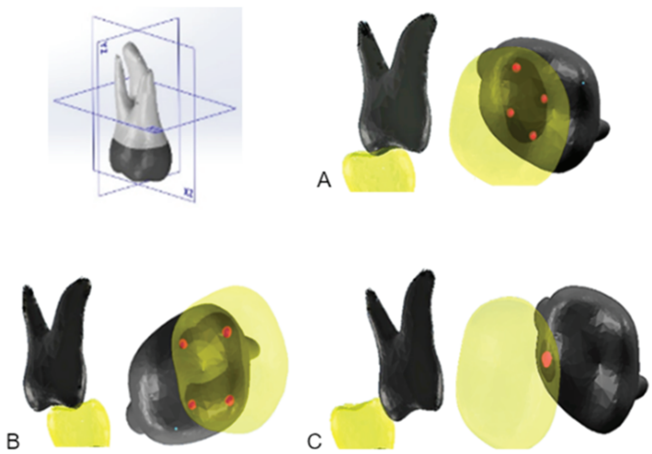

Figure 3. *Models of the first maxillary molar with fragments of the antagonist's tooth during mastication simulations. A, centric occlusion. B, palatal crossbite malocclusion. C, a buccal crossbite malocclusion.*

Utilizing ANSYS software and employing von Mises stress analyses, the findings were represented through a chromatic scale, where colors ranging from blue to red indicated minimum to maximum values. In this investigation, the maximum von Mises stresses in zirconia crowns under different occlusion conditions (expressed in MPa) were pinpointed to differentiate among the von Mises stress fields.

Discussion

This study rejects the null hypothesis, demonstrating that abutment inclination and crown type significantly influence stress distribution in zirconia-based restorations. Finite Element Analysis (FEA) revealed that oblique and horizontal loading directions produced higher von Mises stress magnitudes than vertical loading, especially under malocclusion scenarios (Figure 4).

Stress concentrations were observed beneath loading sites and along marginal areas, shifting with force direction (Figure 5). These findings are consistent with previous research emphasizing the biomechanical impact of load direction during mastication and clenching [14,15]. Normal centric occlusion resulted in lower and more favorable stress distributions compared to crossbite conditions (Figures 5 & 6).

Palatal crossbite conditions yielded the highest stress values across all crown types (Figure 6), likely due to altered occlusal contacts and asymmetric loading, contributing to mandibular displacement and facial asymmetry [16,17]. Buccal crossbites demonstrated broader stress dispersion, potentially from excessive palatal cusp contact and uneven force transmission [18,19].

Malocclusion-induced lateral forces have been associated with increased flexure at the cementoenamel junction, potentially leading to abfraction lesions [20,21]. Additionally, changes in tooth inclination correlate with wider wear areas [22]. Early intervention for unilateral posterior crossbite (UPCB) has shown benefits for mandibular function and symmetry [23,24], though outcomes with rapid maxillary expansion (RME) on muscle activity remain inconclusive [25].

Among all FEA models, horizontal loading produced the highest stress magnitudes, particularly under buccal crossbite conditions (Figure 6), corroborating studies on the critical influence of loading direction [26,27]. Angled abutments exacerbated stress concentrations, increasing the risk of micromotion, crown debonding, or structural failure [28,29].

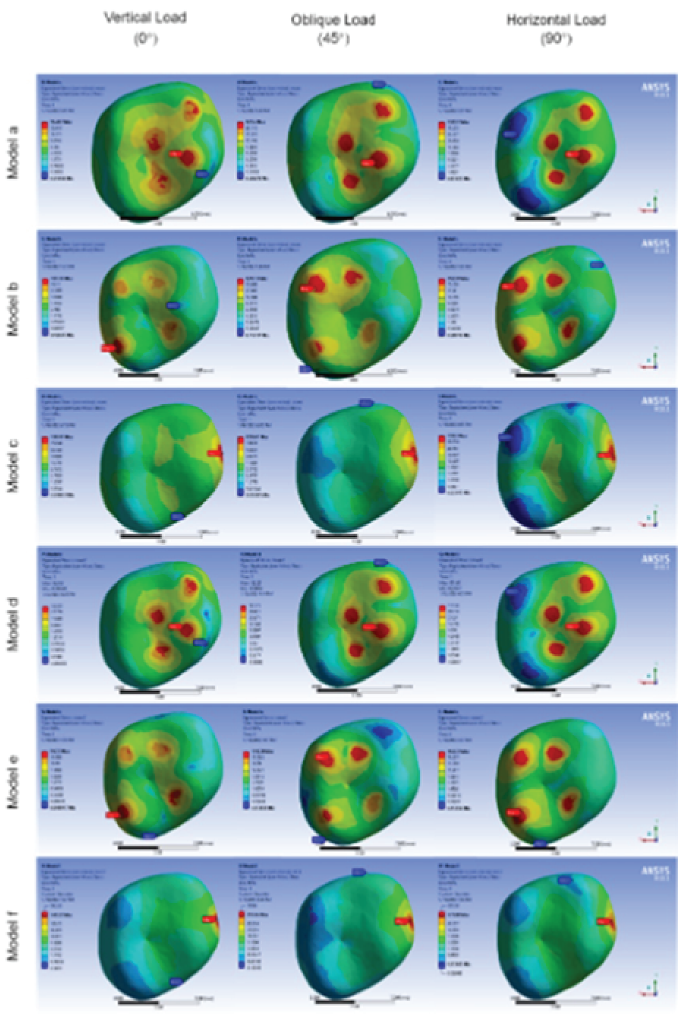

Figure 4. *Contour plots of von Mises stress distributions in all models under vertical, oblique, and horizontal loadings.*

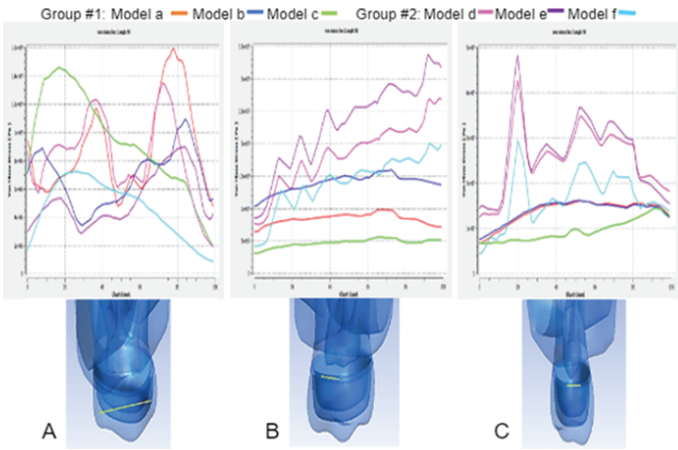

Figure 5. *Von Mises stress distribution. A, Occlusal surface. B, Buccal marginal area. C, Palatal marginal area (yellow lines).*

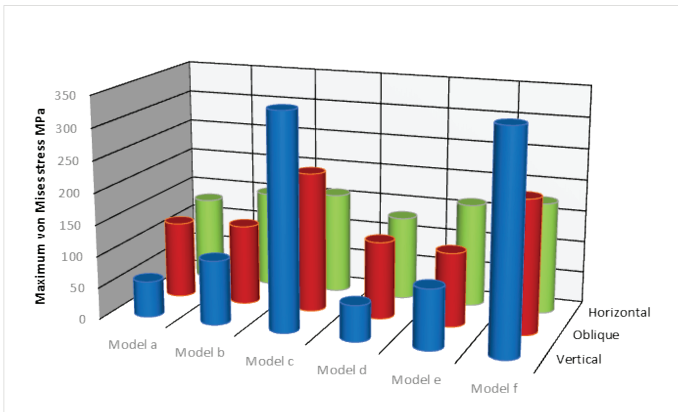

Figure 6. *Maximum von Mises values in zirconia-based crowns loaded under different load directions in different occlusion positions.*

In terms of material behavior, monolithic zirconia crowns exhibited more uniform stress distribution than bi-layered crowns, especially under complex loading directions (Figures. 5B and 5C). This supports previous findings regarding the superior mechanical properties of monolithic zirconia—including strength, hardness, and resistance to crack propagation—due to its transformation-toughening behavior [30-32].

Although veneered zirconia provides esthetic benefits, it demonstrated higher marginal stress under oblique and horizontal loads (Figures 5B, 5C), reinforcing concerns over veneer chipping [33]. These findings indicate that the performance of bi-layered restorations is heavily influenced by the integrity of the core–veneer interface [34]. The monolithic alternative, by eliminating this interface, enhances durability and simplifies fabrication [35-37].

In conclusion, Monolithic zirconia crowns offer more favorable biomechanical performance than bi-layered crowns, particularly in non-ideal occlusal conditions. Future research should move toward integrating occlusal dynamics with functional factors such as posture, mastication, and deglutition to optimize restorative outcomes.

Conclusions

This study demonstrates that abutment inclination, occlusal condition, and crown type significantly affect stress distribution in zirconia restorations. Malocclusion and angled abutments increase stress concentrations, especially under oblique and horizontal loads. Monolithic zirconia crowns showed more favorable stress patterns than bi-layered crowns, supporting their use in complex occlusal scenarios. Clinically, careful selection of crown type and abutment alignment is essential for enhancing restoration durability.

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Authors' contributions

Sara J, Investigation, Data curation, Writing - original draft; Abdulwahab A, Corresponding Author; Supervision; reviewing - original draft; Asma A, Data curation; Ibrahim A, Supervision and Data curation; Mahmoud A, Software and Data analysis.

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Availability of data and materials

The data that support the findings of this study are available from the previously published studies

Declarations

Ethics approval and consent to participate

Approval was obtained from the ethical committee at the faculty of dentistry, Sana'a University, Yemen.

Consent for publication

Informed consent was obtained from all subjects.

Competing interests

The authors declare that they have no competing interests.

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