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Communication

Comparative Stress Evaluation between Bilayer, Monolithic and Cutback All-Ceramic Crown Designs: 3D Finite Element Study

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Abstract: Different all-ceramic crown designs are available to perform indirect restoration; however, the mechanical response of each model should still be elucidated. The study aims to evaluate the stress distribution in three different zirconia crown designs using finite element analysis. Different three-dimensional molar crowns were simulated: conventional bilayer zirconia covered with porcelain, a monolithic full-contour zirconia crown, and the cutback modified zirconia crown with porcelain veneered buccal face. The models were imported to the computer-aided engineering (CAE) software. Tetrahedral elements were used to form the mesh and the mechanical properties were assumed as isotropic, linear and homogeneous materials. The contacts were considered ideal. For the static structural mechanical analysis, 100 N occlusal load was applied and the bone tissue was fixed. Maximum principal stress showed that the stress pattern was different for the three crown designs, and the traditional bilayer model showed higher stress magnitude comparing to the other models. However, grayscale stress maps showed homogeneous stress distribution for all models. The all-ceramic crown designs affect the stress distribution, and the cutback porcelain-veneered zirconia crown can be a viable alternative to adequate function and esthetic when the monolithic zirconia crown cannot be indicated.

Keywords: zirconia; ceramics; finite element analysis; dental materials

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1. Introduction

All-ceramic restorations are widely used in the dental field for their excellent mechanical and aesthetic properties [1]. Among the ceramics, zirconia has excellent mechanical properties but is generally used as infrastructure mainly because of its opacity, requiring a covered with the feldspathic porcelain that has presented optical properties similar to human enamel [2,3]. However, the differences in thermal expansion coefficients generate thermal mismatch between the ceramics, responsible for residual stresses in the system that can lead to early failure of the restorations [4]. These failures include chipping, delamination, debonding, or catastrophic fracture [5,6].

The major factors that can cause bilayer zirconia restorations failures are the low thickness of ceramic and fast cooling [1,5,7]. Besides that, the geometry of the preparation and the restoration design are also factors that influence the mechanical response [8]. Lately, zirconia has been used as a material for monolithic restorations [9]. With the absence of an interface between zirconia and veneering ceramics, this material shows a mechanical behavior far superior to traditional bilayer crowns [10].

A previous study calculated the lifetime prediction of monolithic zirconia crowns, bilayer zirconia crowns covered with porcelain, and a modified porcelain-veneered zirconia crown, suggesting that monolithic zirconia and modified crowns have the lowest failure probabilities [8]. However, the stress analysis has not been elucidated yet and should be performed in order to explain the differences between these all-ceramic crown designs. Therefore, the present study aimed to evaluate the stress distributions in these three different crown geometries using the finite element method. The null hypothesis is that there will be no difference in the stress concentration according to maximum principal stress criteria between conventional crown designs and the cutback modified crown.

2. Methods

A human molar model was designed using computer-aided design (CAD) software (Rhinoceros version 4.0 SR8, McNeel North America, Seattle, WA, USA). For this, the anatomical references were followed to create the surfaces, joined to form each volumetric solid of the first maxillary molar [11]. Next, the crown preparation was constructed with 5.5 mm of height and 12° of occlusal convergence in the axial walls [10].

The external layer of the dental preparation was replicated afterwards as the contacting faces of the preparation and the crown presenting a similar shape to reduce the interference during the mathematical simulation. The final geometries were composed by crown, dental preparation, periodontal ligament, cortical bone and cancellous bone (Figure 1). All bodies were verified as volumetric solids without defects or missing surfaces.

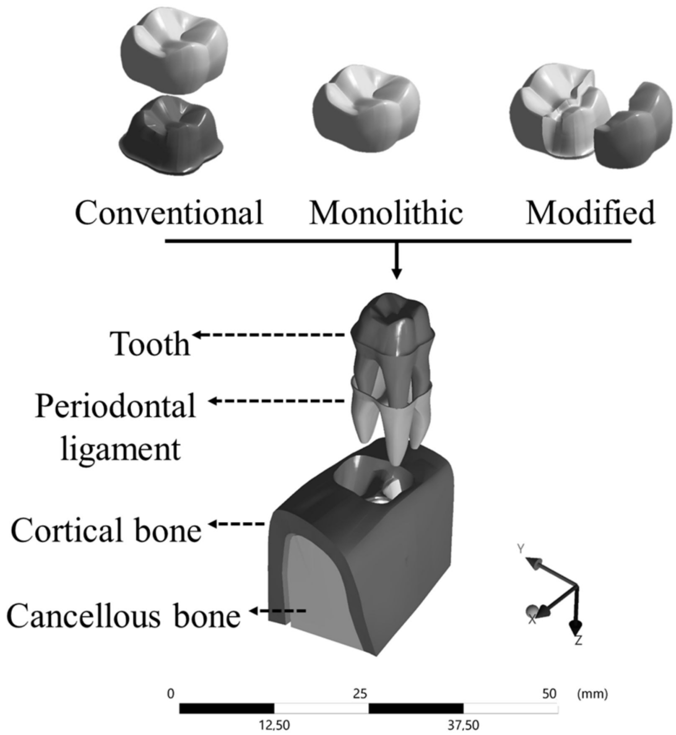

Figure 1. 3D models simulated in the present study with the different crown geometries and volumetric solids.

Different 3D maxillary first-molar full-crown designs were then constructed. In the first model, a traditional bilayer zirconia crown covered with 1.0 mm of porcelain thickness was created using a Boolean difference between both layers; the second model consists of a monolithic zirconia crown, and the third model was considered as a modified porcelain-veneered zirconia crown with 1.0 mm of porcelain in the buccal face. The geometries and crowns are summarized in Figure 1.

After the 3D design process, the models were exported to the computer-aided engineering (CAE) software (Ansys version 15.0; Ansys, Canonsburg, PA, USA) in step format for the preprocessing. The mechanical properties simulated in the present study are described in Table 1 [12–16].

Table 1. Elastic modulus (GPa) and poisson ratio used in the present simulation.

Material	Elastic Modulus (GPa)	Poisson Ratio
Root dentin	18.6	0.32
Zirconia	200	0.30
Feldspathic ceramic	48.7	0.23
Cortical Bone	14	0.30
Cancellous Bone	1.4	0.30
Periodontal Ligament	0.0118	0.45

Note: Value applied in the present simulation.

All contacts among the geometries were considered. Tetrahedral elements formed the mesh, and the total amount of elements and nodes were calculated after the mesh convergence test based on the first principal stress linear trend according to different mesh densities. All materials were considered isotropic, linear and homogeneous for static structural analysis, and the models were fixed at the cancellous bone. According to Figure 2, a load of 100 N load was applied at three different areas [11].

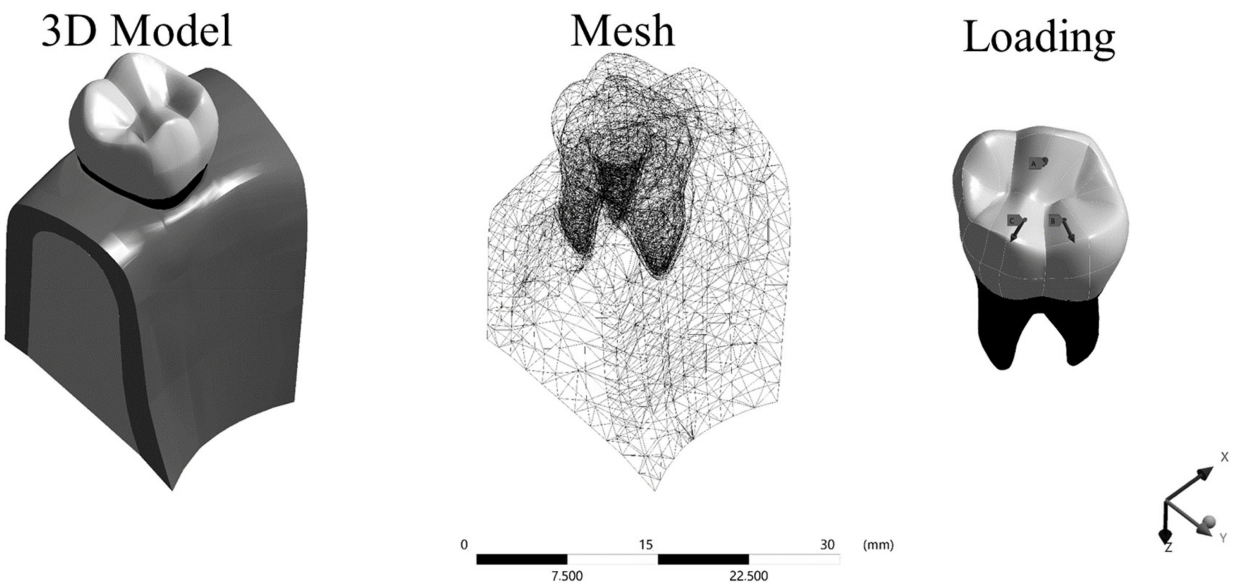

Figure 2. Finite element model exported to the analysis software, after the meshing process and the loading condition applied in this simulation.

The maximum principal stresses (MPS) criteria were used to evaluate the areas of tensile stress concentration between the models. The stress maps were compared by grayscale graphics and the stress peaks (MPa) were recorded in the crown's intaglio surface, mesiodistal section plane and buccolingual section plane.

3. Results

The maximum principal distribution showed a similar stress pattern among the evaluated models, with a significant stress concentration in the singularity area (area in and around the loading application point). To elucidate the difference between the models, different viewports have been applied in the stress map records. In a perspective view (Figure 3), there is a visible difference between the conventional bilayer model and the other simulated models, with the lowest stress concentration at the external surface of the crown.

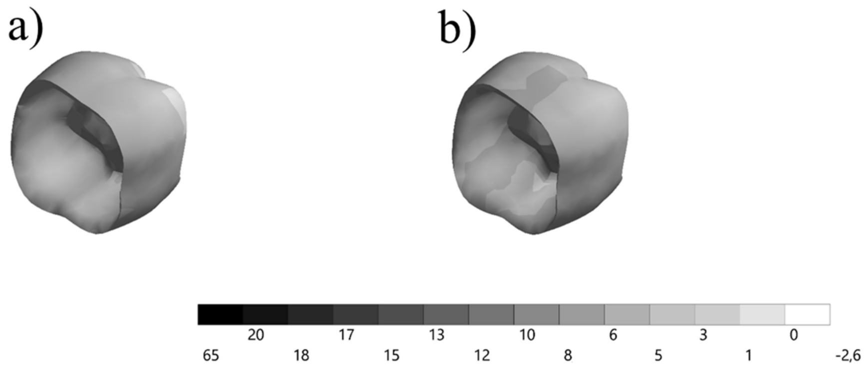

Figure 3. Perspective view of the tensile stress distribution according to the different crown designs. (**a**) Conventional crown, (**b**) monolithic crown and (**c**) modified crown.

However, observing the crown's intaglio surface (Figure 4) there is no visible difference between the models regarding the stress fringes.

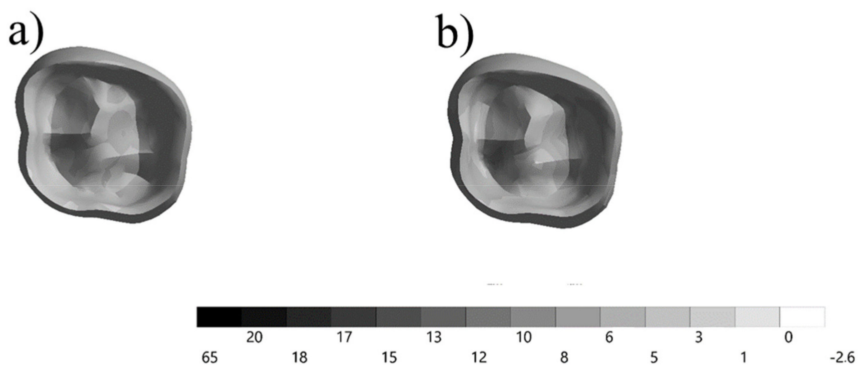

Figure 4. Bottom view of the tensile stress distribution according to the different crown designs. (**a**) Conventional crown, (**b**) monolithic crown and (**c**) modified crown.

Two section planes have been performed in the *X*-axis and *Y*-axis, respectively, named as the mesiodistal cross-section and buccolingual cross-section. In the mesiodistal cross-section, there is a higher stress concentration in the conventional bilayer model, with a visible difference in the interface between zirconia and porcelain material, while the monolithic model and the modified design model did not show a difference between each other, showing lower stress concentration (Figure 5). Regardless of the model, the greater the loading application, the lower the stress magnitude.

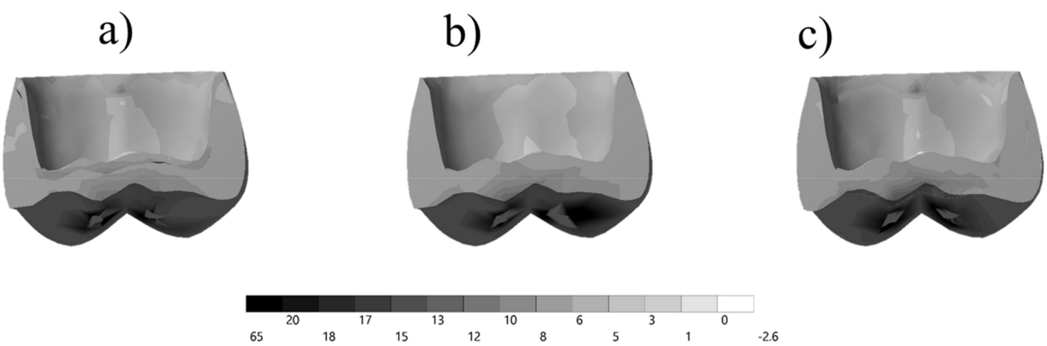

Figure 5. Mesiodistal cross-section of the tensile stress distribution according to the different crown designs. (**a**) Conventional crown, (**b**) monolithic crown and (**c**) modified crown.

Observing the stress trend in the buccolingual cross-section, high stress concentration occurred in the bilayer model, followed by the modified design; the lowest values were found in the monolithic model (Figure 6). The stress evaluation was made considering the tensile stress, represented by the positive values in the stress field, from all viewpoints.

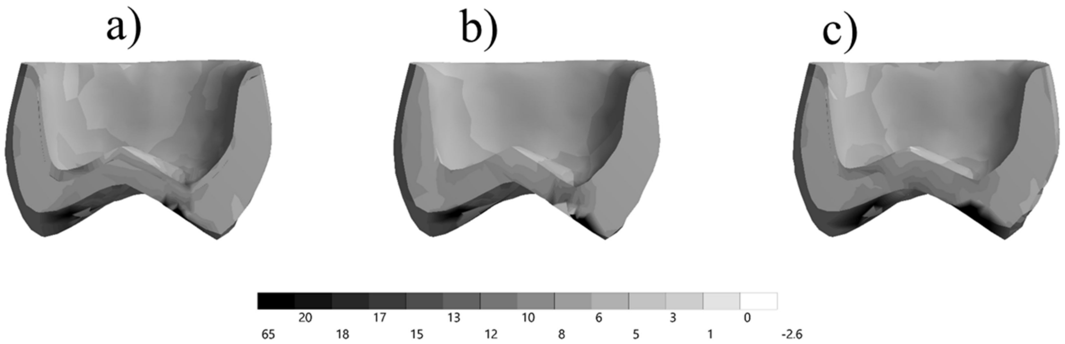

Figure 6. Buccolingual cross-section of the tensile stress distribution according to the different crown designs. (**a**) Conventional crown, (**b**) monolithic crown and (**c**) modified crown.

Despite the homogeneity of stresses in the different crowns designs in the three models, the differences in the stress peaks were assumed as quantitative evaluation. The stress peaks are summarized in Table 2.

Table 2. Stress peaks (MPa) [1] recorded according to the analysis region and crown design.

Region	Crown Design		
	Conventional	**Monolithic**	**Modified**
Intaglio surface	9.9 MPa	8.9 MPa	10.2 MPa
Buccolingual cross-section	6.8 MPa	4.4 MPa	5.7 MPa
Mesiodistal	6.2 MPa	3.1 MPa	3.8 MPa

[1] Value calculated with the stress peak auto-tool.

4. Discussion

The present study evaluated the influence of the stress distribution in three different zirconia crown designs using the finite element analysis. According to the results, the three design of zirconia crowns presented different stress distributions and magnitudes, rejecting the null hypothesis. Through this analysis, the reduced stress concentration observed in the modified crown design could be a promising alternative when the monolithic design cannot be indicated.

The conventional bilayer all-ceramic crown consists of two ceramic materials: the veneering porcelain ceramic that will concentrate some of the stress, showing an inferior elastic modulus to the polycrystalline ceramic infrastructure [1]. In contrast, the monolithic group is composed purely of zirconia material [17]. In addition to the stress concentration being lower in this model, the stress magnitude found and its homogeneous distribution suggest that there would be no fracture for a load of 100 N. These results corroborate with previous findings, in which all monolithic zirconia crowns survived at similar loads applied in the fatigue test [8]. Despite the average human bite force being higher than 100 N, the present study is a linear analysis so that the difference between models will be proportional if the applied load is the same for all of them. The 100 N is a value present in the human chewing cycle, which can be reproduced during in vitro studies.

As a promising model, the modified zirconia crown stress showed a very similar stress trend in relation to the monolithic crown model. This proposed crown design can favor more conservative treatments, reducing the catastrophic failures and porcelain chipping due to the lowest stress magnitude in the ceramics interface.

Modifying the preparation or restoration design may also increase the survival rate of the all-ceramic restorations, especially by increasing the porcelain support [18]. This study corroborates with the in vitro findings of a previous report [8], showing that the modified crown design with greater porcelain support presents an improved stress distribution in the restoration structure.

Despite the report that simpler crown geometries contribute to less stress concentration [19], the present study suggests that the modified crown design should be preferred in aesthetic regions. As the modified crown design has a zirconia framework more flattened than the traditional bilayer design, it could be one of the causes for the promising mechanical response between infrastructure and porcelain material.

As the CAD/CAM manufacturing method allows a high control of the ceramic thickness and design parameters [20], the modified crown design can be planned in CAD without different buccal cutback thickness and machined without issues. In this way, it is possible to perform larger buccal reduction, such as 1.5 mm, for example, for porcelain application or other ceramic-based materials, avoiding unsupported regions that could be suitable for a failure origin [21]. Survival rates of 74% can be found in clinical studies during the first five years for the conventional bilayer crowns [22,23]; therefore, the failure rate for the modified design is expected to be even lower because of the high volume of zirconia that contributes to lower residual stresses between the framework and porcelain layer.

A previous in vitro evaluation [24] performed different all-ceramic crowns and submitted them to thermocycling and mechanical loading prior to fracture load in a compressive test. The authors found that all framework designs showed the potential to withstand physiologic occlusal forces applied in the posterior region. However, the monolithic zirconia crowns showed the highest fracture resistance, followed by the modified porcelain-veneered zirconia crown, and finally, the bilayer design. Therefore, the present study is in agreement with that, explaining that the difference in the fracture load can be caused by the difference in stress concentration and material properties.

A previous study [25] evaluated the biomechanical behavior modified in the framework design for molar zirconia-ceramic using finite element analysis and von-Mises stress as analysis criteria. The authors conclude that different framework designs for zirconia-ceramic crowns can be chosen in order to provide adequate support for the veneering material; however, the cutback design allows the control of the veneering material thickness in order to ensure proper aesthetics, without compromising the strength of the porcelain material. The present study corroborates with this statement, indicating that the tensile stress will also be reduced when the modified design receives a chewing load.

In addition, a finite element evaluation reported that the veneering material can modify the stress distribution and the biomechanical behavior of the cutback design when different aesthetic ceramics were applied [26]. Therefore, despite the promising behavior found in the present study with the use of feldspathic ceramic material, the use of heat-pressed reinforced ceramics (leucite and lithium silicate derivatives) could be another alternative to improve the restoration longevity and should be evaluated in further studies. In addition to the findings reported in the present study, further in vitro tests can provide different information and complementary findings to the purely theoretical results calculated in this finite element study.

5. Conclusions

The cutback modified crown design combines aesthetics without compromising the all-ceramic biomechanical behavior in comparison to the conventional bilayer crown and monolithic zirconia crown. Regardless of the crown design, the highest stresses were located at the contact areas with the loading application and the crown intaglio's surface.

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M.A.B. and J.P.M.T.; data curation, N.d.C.R.; M.M.P. and J.P.M.T.; writing—original draft preparation, N.d.C.R.; G.F.R.; M.M.P. and M.A.B. writing—review and editing, N.d.C.R.; R.M.d.M.; A.L.S.B. and J.P.M.T.; visualization, J.P.M.T.; supervision, R.M.d.M. and A.L.S.B.; project administration, N.d.C.R.; A.L.S.B. and J.P.M.T. All authors have read and agreed to the published version of the manuscript.

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