IDR International Dental Research

Original Article

Effect of margin design changes on stress distribution in zirconia-based full-crown restorations: A three-dimensional finite element analysis

Neslihan Güntekin[1], Reza Mohammadi[2], Ali Rıza Tunçdemir[1]

[1] Necmettin Erbakan University, Faculty of Dentistry, Department of Prosthodontics, Konya, Turkey
[2] Necmettin Erbakan University, Faculty of Dentistry, Konya, Turkey

Abstract

Aim: The aim of this study was to evaluate the effect of margin design changes on the stress distribution in zirconia-based full-crown restorations using three-dimensional finite element analysis.
Methodology: For use in the design of full-crown restorations, tooth number 16 was prepared in chamfer step type on a maxillary tooth jaw model (AG-3: Tipodont, Frasaco, Germany). The prepared tooth was scanned using a desktop scanner, and a three-dimensional finite element analysis model was obtained. Zirconia frameworks are divided into three groups according to the margin design: uniform thickness hood type (Model A), ¾ partial crown form (Model B), and a lingual-band type (Model C). The crown form was completed using feldspathic porcelain as the superstructure material. To determine the stress distribution of the margin design on the restoration, the maximum principal stress (MPa) values under a 600 N vertical load were investigated.
Results: The maximum stress on the zirconia framework was observed in Model A (82.90 MPa), and the maximum stress on the tooth was observed in Model B (49.34 MPa). The maximum stress on the feldspathic porcelain was highest in Model A (21.860 MPa), and the minimum stress on the tooth occurred in Model B (13.33 MPa). In the zirconia framework, the lowest stress was 11.54 MPa (Model B).
Conclusion: The framework design was shown to affect the force generated on the restoration and transmitted to the tooth. The results of the present study will help dentists determine the ideal infrastructure design for zirconia-based restorations. Lingual band designs were found to be successful.

Keywords: Finite element analysis, zirconia, stress distribution, porcelain

Correspondence:

Dr. Neslihan GÜNTEKİN
Necmettin Erbakan University, Faculty of Dentistry, Department of Prosthodontics, Konya, Turkey
E-mail: neslihanvarolnv94@gmail.com

Received: 13 October 2022
Accepted: 15 December 2022

Access Online

DOI:
https://doi.org/10.5577/intdentres.439

How to cite this article: Güntekin N, Mohammadi R, Tunçdemir AR. Effect of margin design changes on stress distribution in zirconia-based full-crown restorations: A three-dimensional finite element analysis. Int Dent Res 2022;12(Suppl.1):10-5. https://doi.org/10.5577/intdentres.439

Introduction

All ceramics based on translucent yttria-stabilized tetragonal zirconia polycrystalline (Y-TZP) have been used in the posterior region due to their mechanical properties developed for fixed dental prostheses (FDPs) (1). They are generally used in clinical practice as traditional double-layer applications and monolithic restorations (2). The two-layer Y-TZP design has been regarded as acceptable in the literature (3). On the other hand, cohesive failures have been reported in the porcelain superstructure of FDPs made from Y-TZP framework material (4, 5).

The differences in the thermal properties of the zirconia framework and porcelain superstructure with regard to the coefficient of thermal expansion (CTE) play a significant role in the formation of high stress, which leads to porcelain fractures (6, 7). Recent studies have reported that the effects of this problem can be minimized by controlling the cooling procedures and using appropriate CTE values (8).

Monolithic restorations may be fabricated using new-generation zirconia materials. As these designs do not have a porcelain superstructure, no fracture is expected (9). However, the aesthetic appearance of these restorations is not comparable to that of porcelain restorations. This is because the level of translucency that may be achieved without tampering with the material's strength is limited (10). The reason for veneering Y-TZP restorations in traditional designs is that the material has poor optical properties. The material should be veneered with a highly aesthetically appealing ceramic material to achieve an acceptable resemblance to the natural tooth structure (11).

The literature shows that the structural reliability of zirconia-based fixed restorations may be improved by changing the framework design (12, 13). The suggested design modifications include expanding the lingual and proximal bands in the framework and designing anatomically shaped frameworks (14, 15). These designs basically aim to equalize the thickness of the porcelain superstructure and prevent the formation of stress in the porcelain layer while cooling.

Semi-monolithic designs are also used in zirconia-based restorations. This design type aims to achieve more aesthetically pleasing restorations without compromising the strength of the monolithic framework. However, this restoration type has a more complicated stress distribution due to the use of various materials and the interfaces between different layers (16).

Finite element analysis (FEA) has been used to assess the mechanical behavior of complex structures and can be used to supplement the in vitro experiments to improve the findings (17, 18). FEA numerically simulates the behavior of various dental restorations, biomaterials, restorative techniques, and prosthetic designs in terms of displacement and stress distribution under varying loading situations. It allows the assessment and quantification of the biomechanical response of restorative materials and the supporting complex dental structures (19-22).

There is no consensus in the literature on which framework design is more advantageous, but finite element analysis (FEA) is considered a robust tool for analyzing stress distributions in restorations fabricated using various materials with different designs (23).

The present study aimed to evaluate the effect of framework designs on stress distribution in zirconia-based fixed dental prostheses under a load of 600 N using a three-dimensional FEA. The null hypothesis is that there is no difference in stress distribution in crowns with different framework designs.

Materials and Methods

Tooth #16 was prepared in a chamfer margin on a maxillary dental model (AG-3: Typodont, Frasaco, Germany) for use in the design of full-crown restorations. The prepared tooth #16 was scanned with a model scanner (Dental Wings 7 Series, Straumann CARES, USA) and imported into the design software (Fig. 1).

Figure 1. Digital image of prepared tooth #16

Margin points were determined using design software (DWOS, Dental Wings, Straumann CARES, USA). The hood uniform thickness (Model A), partial anatomical crown (Model B), lingual band framework (Model C), and superstructure restoration were then designed with the appropriate anatomical form (Fig. 2).

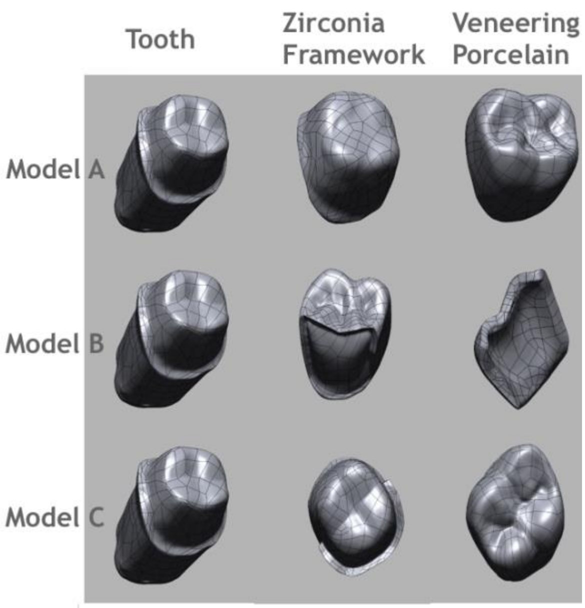

Figure 2. Design images

The resulting design was exported as an STL file. The required adjustments were made by importing the file into the relevant software (Geomagic Design x 2020/0.3) to eliminate potential errors and make it suitable for FEA. The final STP files were then obtained. The meshing processes were completed using the Solidworks 2013 software (Solidworks Corp., USA) for the composition of both the anchorage and the designed restoration models. The STP files were imported into the relevant FEA software (2020 Dassault Systèmes Simulia Corp., Johnston, RI, USA), and the designed scenario was applied.

The numbers of elements and nodes by model are shown in Table 1.

Table 1. Nodes and elements of the tested groups

Model	Total elements	Total nodes	Mesh type
Model A	1143733	221433	Linear tetrahedral elements of C3D4
Model B	1084558	211785	Linear tetrahedral elements of C3D4
Model C	859459	164380	Linear tetrahedral elements of C3D4

The average masticatory force was designed and implemented as the transmission of a 600 N load. The properties of the materials are presented in Table 2. All materials were deemed isotropic linear elastic, and the effect of the periodontal ligament was ignored. Maximum principal stress (MPa) values were reported to analyze the effect of restoration framework design on stress distribution.

Table 2. Mechanical properties of the materials and structures used in this study

Material	Elastic modulus (GPa)	Poisson's ratio	Tensile strength (MPa)
Dentin	18.6	0.31	
Translucent zirconia	210	0.30	1000
Porcelain	74	0.19	100

Results

This study analyzed the effects of different zirconia-based framework designs on stress distribution on the tooth, zirconia framework, and veneering porcelain under a load of 600 N. The maximum tensile strengths are presented in Table 3, and the values are graphically represented in Figure 3.

Model A exerted the maximum stress on the zirconia framework (82.90 MPa), while Model B caused the maximum stress on the tooth (49.34 MPa). Model A also posed the maximum stress on the veneering porcelain (21.860 MPa). Model B had the minimum stress on the tooth and veneering porcelain (13.33 and 1.076 MPa, respectively), and Model C exerted the minimum stress on the zirconia framework (11.54 MPa). The patterns of stress distribution are illustrated in Figure 4.

Table 3. Maximum principal stress (MPa) values in restoration, enamel, and dentin under loads for Model A

Model	Tooth	Veneering porcelain	Zirconia framework
Model A	45.04	21.860	82.90
Model B	49.34	1.076	11.54
Model C	13.33	6.003	55.34

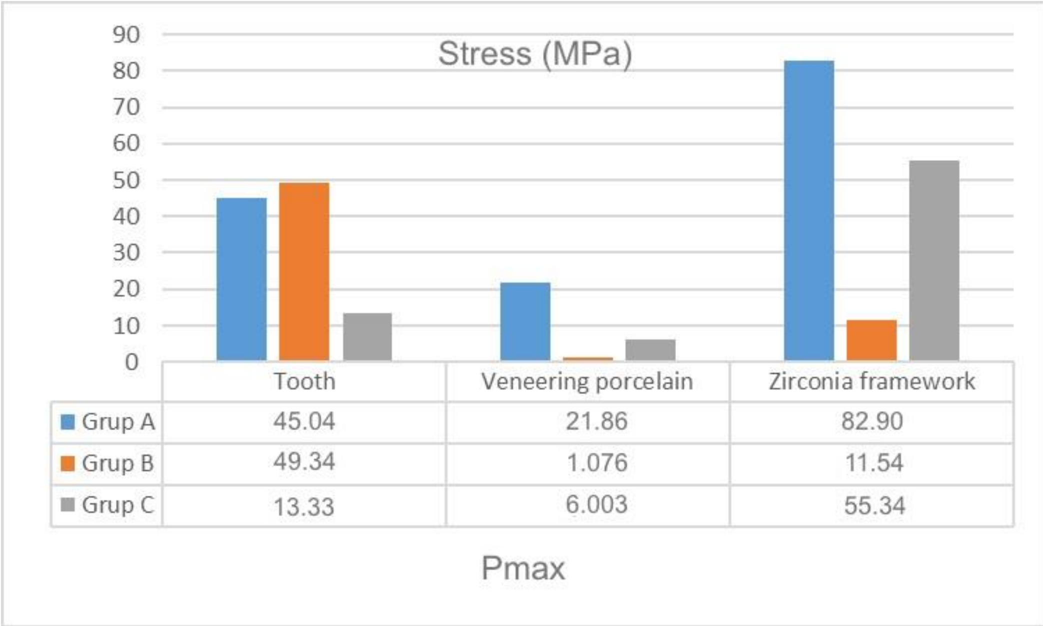

Figure 3. Graphical representation of maximum principal stress values

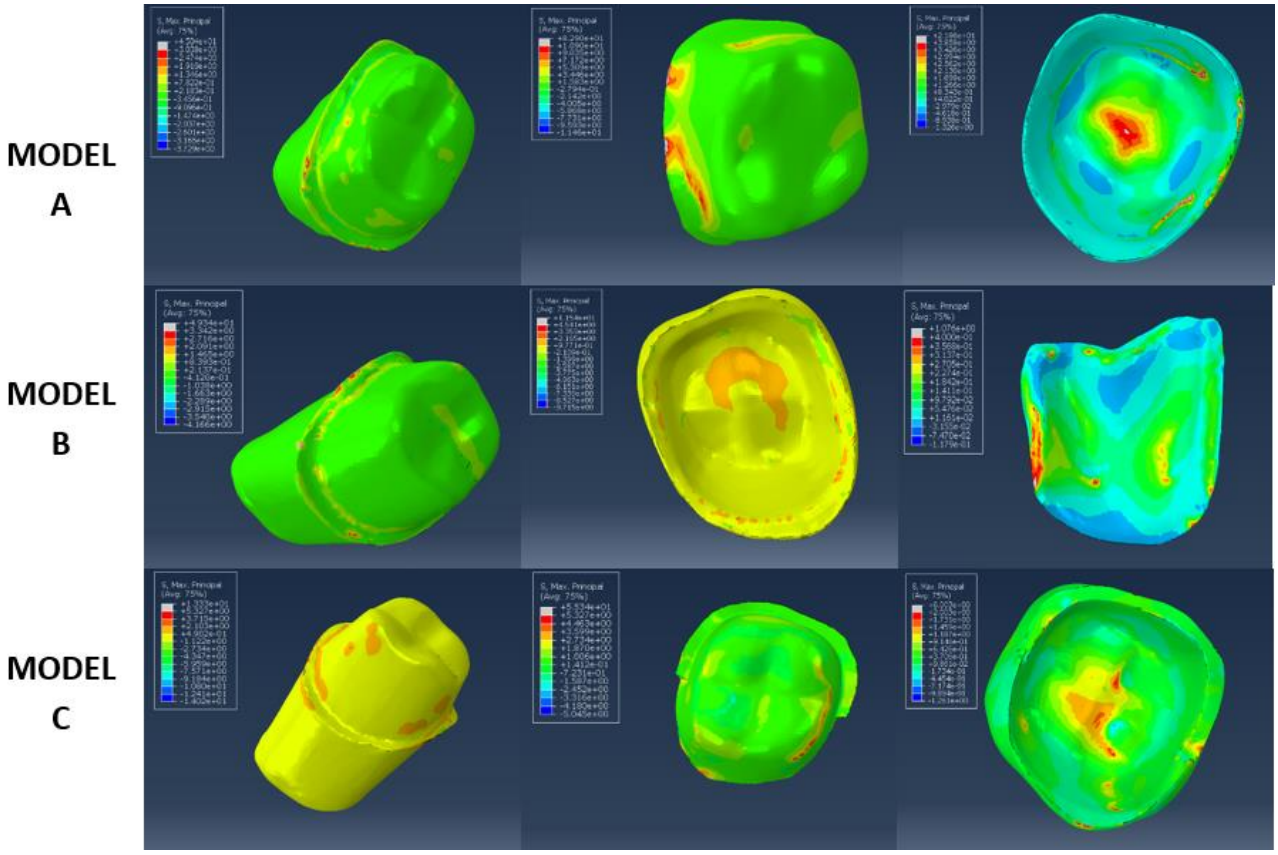

Figure 4. Patterns of maximum principal stress distribution

Discussion

This in vitro study examined the effects of different framework designs on stress distribution in single-crown restorations. The null hypothesis was evaluated and rejected given the differences in stress distributions on both the tooth and the restoration depending on framework shape.

In all the conditions where the coefficient of thermal expansion of the porcelain was lower than that of the framework material, stress occurred within the porcelain adjacent to the framework material. The thermal cycle that takes place in the mouth while eating and drinking is an undesirable result, as it facilitates the onset of cracks on the surface of teeth (4).

The maximum bite force differs among patients, and we have noted some excessive forces that may not fall within the normal range in certain individuals. The highest force measured by researchers in a patient is 4000 N, and the second-highest is 2000 N (24). However, it is infeasible to target similar levels of biting force when designing restorations because the vast majority of patients rarely reach forces equal to or higher than 1000 N. For this reason, the current study implemented a load of 600 N, which can be considered an average value.

This research also fabricated restorations with a standard degree of preparation, regardless of the differences in framework design. This means that the total thickness of the crowns was the same across all the groups. In other words, the thicker the veneering porcelain, the thinner the supporting framework material. This phenomenon may have played an important role in the results of the study (25). The probability of cohesive failure in a restoration under stress during loading increases in direct proportion to the volume of porcelain in the designed restoration (16). This observation was confirmed in the current work, which demonstrated that the stress acting on a restoration was at a maximum level in Model A. Similarly, the absence of porcelain on the occlusal surface where force was applied ensured that the force acted entirely on the zirconia framework in Model C, which is why the maximum stress on zirconia occurred in this group.

In some cases, an imperative is to use thick layers of porcelain to achieve aesthetically appealing results (≥0.5 mm). Using lingual band designs in Model C instead of hood frameworks in Model A will reduce the stress on both veneering porcelain and zirconia. A similar study found that fracture resistance improves in restorations wherein the occlusal plate is fabricated from zirconia to protect the buccal porcelain from high occlusal loads (16). This is also the case in Model B in the present study. However, manufacturing these semi-monolithic designs is more complicated and time-consuming for dental technicians.

A limitation of the current study is that the in vitro test could not fully simulate in vivo conditions (e.g., the periodontal ligament and cement were not modeled). In addition, although homogeneous and isotropic materials could not be obtained in vivo, the materials used in the study were accepted to be so. Finally, we assessed a single loading protocol, and further research is needed to examine relevant behaviors under different loads.

Conclusions

We drew the following conclusions on the basis of the FEA findings:

1. The stress on both frameworks and veneering porcelain increases in frameworks fabricated in hood form.
2. In conditions wherein the thickness of porcelain needs to be increased, it is acceptable to use frameworks with lingual bands.
3. If the occlusal plate is fabricated from zirconia and the buccal side is made of porcelain, these crowns may be used in cases where the distance is short and the strength of zirconia is to be utilized.

Acknowledgments: This study has been presented at the Necmettin Erbakan University 2nd International Dentistry Congress held between October 1-3, 2022.

Peer-review: Externally peer-reviewed.

Author Contributions: Conception – N.G.; Design – N.G., R.M.; Supervision – N.G.; Materials – N.G.; Data Collection and/or Processing – N.G., A.R.T.; Analysis and/or Interpretation – R.M.; Literature Review – N.G., R.M.; Writer – N.G.; Critical Review – A.R.T.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study has received no financial support.

References

1. Miyazaki T, Nakamura T, Matsumura H, Ban S, Kobayashi T. Current status of zirconia restoration. J Prosthodont Res. 2013;57(4):236-261. https://doi.org/10.1016/j.jpor.2013.09.001
2. Denry I, Kelly JR. State of the art of zirconia for dental applications. Dent Mater. 2008;24(3):299-307. https://doi.org/10.1016/j.dental.2007.05.007
3. Le M, Papia E, Larsson C. The clinical success of tooth- and implant-supported zirconia-based fixed dental prostheses. A systematic review. J Oral Rehabil. 2015;42(6):467-480. https://doi.org/10.1111/joor.12272
4. Swain M V. Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures. Acta Biomater. 2009;5(5):1668-1677. https://doi.org/10.1016/j.actbio.2008.12.016
5. Pjetursson BE, Sailer I, Makarov NA, Zwahlen M, Thoma DS. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part II: Multiple-unit FDPs. Dent Mater. 2015;31(6):624-639. https://doi.org/10.1016/j.dental.2015.02.013

6. Fischer J, Stawarczyk B, Tomic M, Strub JR, Hämmerle CHF. Effect of thermal misfit between different veneering ceramics and zirconia frameworks on in vitro fracture load of single crowns. Dent Mater J. 2007;26(6):766-772. https://doi.org/10.4012/dmj.26.766
7. Bonfante EA, Rafferty B, Zavanelli RA, et al. Thermal/mechanical simulation and laboratory fatigue testing of an alternative yttria tetragonal zirconia polycrystal core-veneer all-ceramic layered crown design. Eur J Oral Sci. 2010;118(2):202-209. https://doi.org/10.1111/j.1600-0722.2010.00724.x
8. Paula VG, Lorenzoni FC, Bonfante EA, Silva NRFA, Thompson VP, Bonfante G. Slow cooling protocol improves fatigue life of zirconia crowns. Dent Mater. 2015;31(2):77-87. https://doi.org/10.1016/j.dental.2014.10.005
9. Furtado de Mendonca A, Shahmoradi M, de Gouvêa CVD, De Souza GM, Ellakwa A. Microstructural and Mechanical Characterization of CAD/CAM Materials for Monolithic Dental Restorations. J Prosthodont. 2019;28(2):e587-e594. https://doi.org/10.1111/jopr.12964
10. Zhang Y. Making yttria-stabilized tetragonal zirconia translucent. Dent Mater. 2014;30(10):1195-1203. https://doi.org/10.1016/j.dental.2014.08.375
11. Conrad HJ, Seong WJ, Pesun IJ. Current ceramic materials and systems with clinical recommendations: A systematic review. J Prosthet Dent. 2007;98(5):389-404. https://doi.org/10.1016/S0022-3913(07)60124-3
12. Bakitian F, Seweryniak P, Papia E, Larsson C, Vult von Steyern P. Fracture strength of veneered translucent zirconium dioxide crowns with different porcelain thicknesses. Acta Biomater Odontol Scand. 2017;3(1):74-83. https://doi.org/10.1080/23337931.2017.1403288
13. Ambré MJ, Aschan F, von Steyern PV. Fracture strength of yttria-stabilized zirconium-dioxide (Y-TZP) fixed dental prostheses (FDPs) with different abutment core thicknesses and connector dimensions. J Prosthodont. 2013;22(5):377-382. https://doi.org/10.1111/jopr.12003
14. Wang G, Zhang S, Bian C, Kong H. Effect of thickness ratio on load-bearing capacity of bilayered dental ceramics. J Prosthodont. 2015;24(1):17-24. https://doi.org/10.1111/jopr.12169
15. Silva NRFA, Bonfante E, Rafferty BT, et al. Conventional and Modified Veneered Zirconia vs. Metalloceramic: Fatigue and Finite Element Analysis. J Prosthodont. 2012;21(6):433-439. https://doi.org/10.1111/j.1532-849X.2012.00861.x
16. Bakitian F, Seweryniak P, Papia E, Larsson C, Von Steyern PV. Effect of different semimonolithic designs on fracture resistance and fracture mode of translucent and high-translucent zirconia crowns. Clin Cosmet Investig Dent. 2018;10:51-60.https://doi.org/10.2147/CCIDE.S157118
17. Yeniçeri Özata M, Adıgüzel Ö, Falakaloğlu S. Evaluation of stress distribution in maxillary central incisor restored with different post materials: A three-dimensional finite element analysis based on micro-CT data. Int Dent Res 2021;11(3):14957. https://doi.org/10.5577/intdentres.2021.vol11.no3.3
18. Tatarciuc M, Maftei GA, Vitalariu A, Luchian I, Martu I, Diaconu-PopaD. Inlay-retained dental bridges – a finite element analysis. Appl Sci.2021;11:3770.27. https://doi.org/10.3390/app11093770
19. Tekin S, Adıgüzel Ö, Cangül S. An evaluation using micro-CT data of the stress formed in the crown and periodontal tissues from the use of PEEK post and PEEK crown: A 3D finite element analysis study. Int Dent Res 2018;8(3):144-50. https://doi.org/10.5577/intdentres.2018.vol8.no3.8
20. Assaf J, Hardan L, Kassis C, Bourgi R, Devoto W, Amm E, et al.Influence of resin cement thickness and elastic modulus on the stressdistribution of zirconium dioxide inlay-bridge: 3D finite elementanalysis. Polymers (Basel). 2021;13:3863. https://doi.org/10.3390/polym13223863
21. Keulemans F, Shinya A, Lassila LV, Vallittu PK, Kleverlaan CJ, et al. Three-dimensional finite element analysis of anteriortwo-unit cantilever resin-bonded fixed dental prostheses. Sci World J.2015;2015:864389. https://doi.org/10.1155/2015/864389
22. Zengingül Aİ, Göncü Başaran E, Çelik H. Finite elements analysis of stresses formed in core and spongious bone tissue by restored implanted fixed prostheses with Polyetheretherketone (PEEK) and fiber-reinforced composite. Int Dent Res 2021;11(Suppl.1):250-8. https://doi.org/10.5577/intdentres.2021.vol11.suppl1.37
23. Styranivska O, Kliuchkovska N, Mykyyevych N. Comparison of using different bridge prosthetic designs for partial defect restoration through mathematical modeling. Eur J Dent. 2017;11(3):345-351. https://doi.org/10.4103/ejd.ejd_72_17
24. Gibbs CH, Mahan PE, Mauderli A, Lundeen HC, Walsh EK. Limits of human bite strength. J Prosthet Dent. 1986;56(2):226-229. https://doi.org/10.1016/0022-3913(86)90480-4
25. Nakamura K, Harada A, Inagaki R, et al. Fracture resistance of monolithic zirconia molar crowns with reduced thickness. Acta Odontol Scand. 2015;73(8):602-608. https://doi.org/10.3109/00016357.2015.1007479