ATATÜRK ÜNİVERSİTESİ YAYINLARI
ATATURK UNIVERSITY PUBLICATIONS

Research Article *Araştırma Makalesi* DOI: 10.17567/currresdentsci.1436067

Mechanical Evaluation of Two Different Zirconia-Reinforced Lithium Silicate Ceramics: A Finite Element Analysis

İki Farklı Zirkonyum Takviyeli Lityum Silikat Seramiğin Mekanik Değerlendirmesi: Sonlu Elemanlar Analizi

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ABSTRACT

Objective: The aim of the study is to evaluate the stress distribution of zirconia-reinforced lithium silicate all-ceramic fixed partial dentures under occlusal loading; in terms of material, restoration, and supporting type.

Methods: Six different models were analyzed; tooth-supported anterior crown, tooth-supported posterior crown, tooth-supported 3-unit bridge, implant-supported anterior crown, implant-supported posterior crown and implant-supported 3-unit bridge. Milling and pressable zirconia-reinforced lithium silicate were used in each model. Structural analyses were simulated with finite element analysis under vertical and oblique loading to evaluate the von Mises and minimum principal stresses.

Results: Tooth-supported restorations showed lower stress values than implant-supported forms of the same restoration. Stresses were higher and distributed over a larger surface under oblique loading compared to vertical loading. Overall stresses generated on the single crown models were higher than the stresses generated on the bridge models. Implant-supported bridge model under oblique loading shows the highest stress. However both milling and pressable forms of zirconia-reinforced lithium silicate didn't make a difference on the stress concentration and distribution areas.

Conclusion: The stress distribution and mechanical behavior of models was influenced by the type of restoration, direction of the force, and the number of units. However, no significant difference was found between milling and pressable zirconia-reinforced lithium silicate ceramic in terms of the stress values on the restorations.

Keywords: Dental ceramic, finite element analysis, fixed partial dentures, implant-supported single crown, zirconia-reinforced lithium silicate

ÖZ

Amaç: Çalışmanın amacı, zirkonyumla güçlendirilmiş lityum silikat tam seramik sabit parsiyel protezlerin oklüzal yükleme altındaki stres dağılımını; malzeme, restorasyon ve destek tipi açısından değerlendirmektir.

Yöntemler: Diş destekli anterior kron, posterior kron, 3 üyeli köprü ve implant destekli anterior kron, posterior kron, 3 üyeli köprü olmak üzere altı farklı model analiz edildi. Her modelde frezelenebilir ve preslenebilir zirkonyum takviyeli lityum silikat kullanıldı. Sonlu elemanlar analizi, dikey ve oblik yükleme altında simüle edilerek von Mises ve minimum asal stresler değerlendirildi.

Bulgular: Dikey yüklemeye kıyasla, oblik yükleme altında stresler daha yüksekti ve daha geniş alanlı dağılıma sahipti. Diş destekli restorasyonlar, aynı restorasyonun implant destekli formlarından daha düşük stres değerleri gösterdi. Tek kron modellerinde oluşan stresler, köprü modellerinde oluşan streslerden daha yüksekti. İmplant destekli köprü modeli eğik yükleme altında en yüksek stresi gösterirken hem frezeleme hem de preslenebilir zirkonyum takviyeli lityum silikat formları stres konsantrasyonu ve dağılım alanları üzerinde bir fark görülmedi.

Sonuç: Modellerin stres dağılımı ve mekanik davranışı restorasyon tipi, kuvvet yönü ve üye sayısından etkilenmiştir. Ancak, restorasyonlardaki stres değerleri açısından frezeleme ve preslenebilir zirkonyum takviyeli lityum silikat seramik arasında önemli bir fark bulunamamıştır.

Anahtar Kelimeler: Dental seramik, sonlu elemanlar analizi, sabit protezler, implant destekli tek kron, zirkonyum takviyeli lityum silikat.

Geliş Tarihi/Received	12.02.2024
Revizyon Talebi/Revision Requested	19.02.2024
Son Revizyon/Last Revision	22.03.2024
Kabul Tarihi/Accepted	29.03.2024
Yayın Tarihi/Publication Date	20.04.2025

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Cite this article: Botsalı M, Dikicier S, Botsalı H, Atay A. Mechanical Evaluation of Two Different Zirconia-Reinforced Lithium Silicate Ceramics: A Finite Element Analysis. *Curr Res Dent Sci.* 2025;35(2):148-153.

INTRODUCTION

Metal-ceramic fixed partial dentures (FPDs) were thought to combine both the aesthetic properties of ceramics and the high mechanical properties of metal frameworks, before the all-ceramic systems.[1] However, developing CAD/CAM technologies and increasing aesthetic expectations have increased the demand for metal-free materials with translucency and optical properties close to natural teeth, and thus all-ceramic restorations with high aesthetic properties and biocompatibility have been developed. In addition to providing aesthetic expectation, it is aimed to increase the mechanical properties and the clinical indications of the materials.[2]

Zirconia has used for FPDs because of its high flexural and mechanical strength. Despite its superior aesthetic properties, lithium disilicate (LDS) is not more strength than zirconia. Zirconia-reinforced lithium disilicate (ZLS) ceramics is produced by combining with zirconia and LDS in order to keep aesthetic and mechanical properties together.[3] In most studies examining the success of ZLS; ZLS blocks were compared with zirconia and LDS blocks on single crowns and it was evaluated that ZLS is one of the preferred ceramic materials in clinical use and reliable in single crowns.[4,5] The indications for ZLS ceramics have been expanded and their use has been validated for both implant-supported and tooth-supported 3-unit FPDs up to the second premolar, as well as for anterior and posterior single crowns.[6,7]

The CAD/CAM milling block form of ZLS, which attracts attention with its expanding of indications in current clinical use, was first introduced to the market. It is thought that different production techniques can improve the mechanical properties, the ingot form was also produced.[7,8] Since there are not enough studies examining the effect of these differences in the manufacturing technique of ZLS on mechanical strength, these materials were used in the study and evaluated on all FPDs within the ZLS indications.

The mechanical performance of dental ceramics can be approached experimentally by evaluating the strength values reflecting the mechanical behavior. Besides experimental tests to compare mechanical strength of ceramic restorations with different designs; the finite elements analysis (FEA) was also used to predict the biomechanical behavior of post-loading restorations.[9]

Generally, in many studies using the FEA method,[10–12] the biomechanical properties of different restorative or prosthetic materials were evaluated on a single same model. These studies mostly made biomechanical comparisons for materials by changing the ceramics on the single crown. In fact, in clinical use, a material has various FPD indications, whether single-unit or multi-unit, and it is important to estimate the stress generated in this material. However, there are insufficient data to evaluate the stress occured on different types of FPDs made by same material. Therefore, the aim of this study is to evaluate the biomechanical behavior of all FPDs within the indications of milling and pressing ZLS. The null hypothesis was that the stress distributions on the FPDs are affected by restoration type and the milling or pressable forms of the ZLS.

METHODS

In this study, maxillary canine, mandibular first molar, mandibular canine, mandibular first and second premolar teeth, enamel, dentin, periodontal ligament, bone tissue (cortical and cancellous), resin cement, titanium implant and abutment were analysed by 3D FEA software. Prepared teeth models were obtained from tomography data using Mimics® (Materialise, Belgium) tissue modeling program. Standard tesselation language (STL) files acquired by this program were imported into CAD software (SOLIDWORKS® Dassault Systemes, ABD). Imported STL files as graphic data in CAD environment was converted to solid model utilizing surface modeling tools.

Bone-level implants are used in the anterior due to providing cervical aesthetic, and there are studies showing that bone-level and tissue-level implants have similar clinical success.[13] For this reason, bone-level implants were designed on all models for standardizing the implants in the study. For implant-supported FPDs 4.1x10 mm bone-level implant and standard titanium dental abutment (Straumann AG, Basel, Switzerland) were selected. In implant-supported FPDs depending on the standard abutment size, the restoration thicknesses reach 2.3 mm on the axial surfaces in anterior and premolar crowns and up to 4 mm on the posterior crown. Tooth-supported FPDs was determined as 2 mm-in thickness for crowns, 16 mm^2 (4 mm x 4 mm) connector cross-section for bridge, and 8 mm-in width pontic, and 1 mm rounded shoulder finish line was used. Resin cement thickness was chosen 50 µm. Maxillary canine for anterior crown, mandibular first molar for posterior crown, mandibular canine and mandibular second premolar teeth as abutments for 3-unit bridge were selected. Each restoration was designed both tooth-supported and implant-supported. Thus, 6 models were obtained; TA: Tooth-supported anterior crown, TP: Tooth-supported posterior crown, TB: Tooth-supported 3-unit bridge, IA: Implant-supported anterior crown, IP: Implant-supported posterior crown, IB: Implant-supported 3-unit bridge (Figure 1).

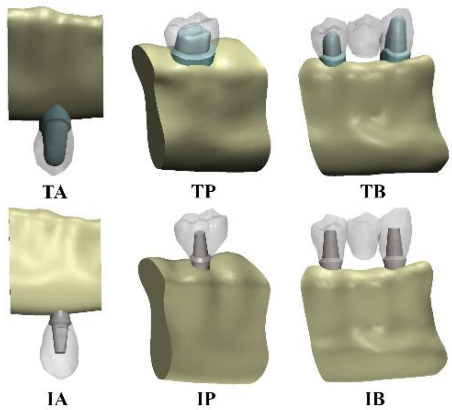

Figure 1. 3D models of the FPDs (TA: tooth-supported anterior crown, TP: tooth-supported posterior crown, TB: tooth-supported 3-unit bridge, IA: implant-supported anterior crown, IP: implant-supported posterior crown, IB: implant-supported 3-unit bridge)

Solid models were transferred to SOLIDWORKS Simulation (SOLIDWORKS® Dassault Systemes, ABD) software for FEA. Solid models were converted into mathematical models with pre-processing stages such as defining material properties, determining contact relationships, determining boundary conditions and creating a finite element mesh before FEA. The Young's modulus and Poisson's ratio values, which reflects the mechanical properties of each materials, were defined primarily based on the literature and manufacturer's instructions (Table 1).[14–19] In order to compare the results at the end of the analysis, the flexural strength value provided by the manufacturer was also defined in practice as a strength parameter. VITA Suprinity PC (Vita Zahnfabrik, Bad Säckingen, Germany) CAD/CAM milling ZLS, with a flexural strength of 420 MPa and VITA Ambria (Vita Zahnfabrik, Bad Säckingen, Germany), heat-pressed ZLS with a flexural strength of 550 MPa were selected. VITA Ambria symbolized by A and VITA Suprinity PC by S. Boundary conditions were implemented to fix the cortical bone so that it would not cause rigid body dynamics. Contact relationships were defined as bonded. Thus solving analyses of ZLS single crown and 3-unit bridge FPDs after completed preprocessing. Since the magnitude and direction of occlusal loads are important in predicting the survival rate of materials used for FPDs, 500 N load has applied to the models, vertically and 45° inclined (direction from lingual to buccal) to simulate the maximum occlusal loading during chewing. When it comes to defining how these loads affect, contact with foods were acknowledged acting on the palatal surface of the anterior crown[16] and the occlusal surface of the posterior crown[12] (Figure 2). Because the loadings implemented in the study would not cause large displacements, the analyses were solved linearly and statically. Finite element mesh was generated by second order tetrahedral elements. The mesh element and node numbers were given in Table 2 and the mesh models were also shown in Figure 3. Finally, analysis results were acquired as displacement quantity and the von Mises stress values were calculated mathematically by the software.

Since the study was a computer-assisted experimental study in which the patient did not have, ethics committee approval and informed consent were not obtained.

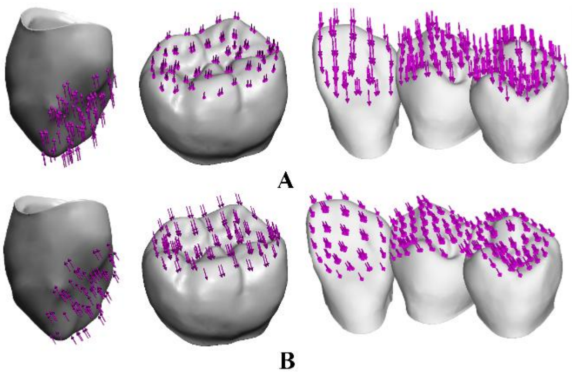

Figure 2. Directions of loading for FEA; A) vertical loading, B) oblique loading

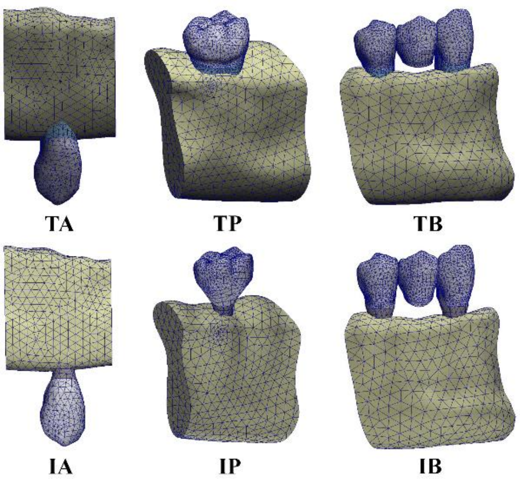

Figure 3. Meshed data of finite element models

Table 1. Mechanical properties of the materials

Material	Young's Modulus (GPa)	Poisson's Ratio
Enamel[14]	84.1	0.33
Dentin [15]	18.6	0.32
Periodontal Ligament[16]	0.05	0.45
Cancellous Bone[17]	1.37	0.30
Cortical Bone[17]	13.7	0.30
Titanium[18]	110	0.30
VITA Suprinity PC[6]	70	0.21
VITA Ambria[7]	100	0.20
Resin Cement[19]	8.3	0.35

Table 2. Element and node numbers of the models

Models	Element numbers	Node numbers
TA	18.472	29.317
TP	38.863	59.282
TB	50.012	77.503
IA	23.830	37.248
IP	34.470	52.650
IB	58.468	90.796

RESULTS

Figure 4 present von Mises stress values observed within the FPDs. Higher stress values were observed under oblique loading than vertical loading in each models regardless of the form of ZLS (A or S), supporting type (tooth-suported or implant-supported) or number of units (single-unit or 3-unit). According to the analysis results, when the supporting type was compared, von Mises stress values on the restorations under same loading were higher on the implant-supported models (I) compared to the prepared tooth-supported models (T) of the same restoration. This means that IA models have more stress than TA, IP models have more stress than TP, and IB models have more stress than TB.

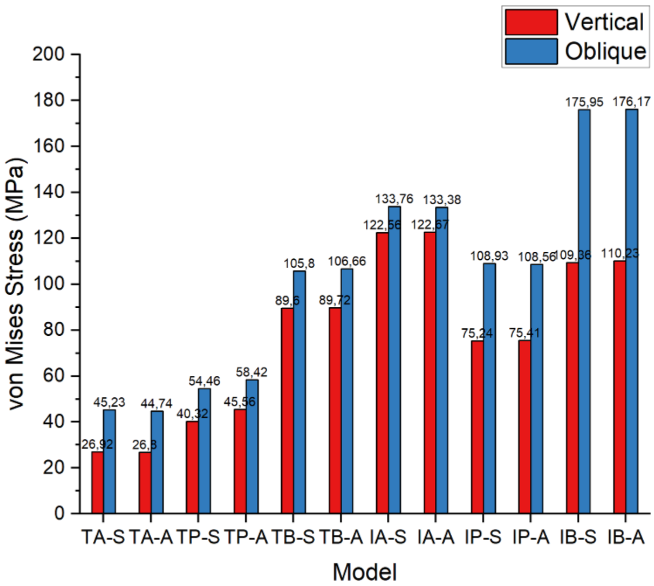

Figure 4. von Mises stresses results for the studied models with 500 N vertical and oblique loads (TA: tooth-supported anterior crown, TP: tooth-supported posterior crown, TB: tooth-supported 3-unit bridge, IA: implant-supported anterior crown, IP: implant-supported posterior crown, IB: implant-supported 3-unit bridge, S: VITA Suprinity PC, A: VITA Ambria).

When the unit numbers of FPDs are evaluated, the highest stress occurs in 3-unit bridges (TB-S, TB-A, IB-S and IB-A) compared to single-unit FPDs. Under both loading conditions, stresses of the TB models were higher than TA and TP models, and IB models were higher than IA and IP models. When all the results were examined, it was seen that the implant-supported bridge model (IB) had the highest von Mises stresses under oblique loading (IB-S: 179.95 MPa; IB-A: 176.17 MPa). However, when VITA Suprinity and VITA Ambria were compared, there was no significant difference between the S and A forms of FPDs in terms of the amount of stress on the restorations.

Figure 5 shows the areas of von Mises stresses distributed on the inner surfaces of FPDs under oblique loading. It was observed that the areas of increased stress in restorations made of milled and heat-pressed ZLS showed significant similarities. This means that the same amount of stress occurs in the same restoration areas. It was observed that maximum stress was generated on the inner surface of the restoration in the S and A forms of each model. As a result of this study, the stress is highest at the abutment-restoration and tooth-restoration interfaces of FPDs. Another area where the stress is highest is the occlusal surface of the FPDs. These are the surface on which the stress is applied. It was also observed that in 3-unit- FPDs, the maximum stress was observed in the connectors regardless of the supporting type. According to the biomechanics of bridges, these are the areas most exposed to stress because they allow stretchin.

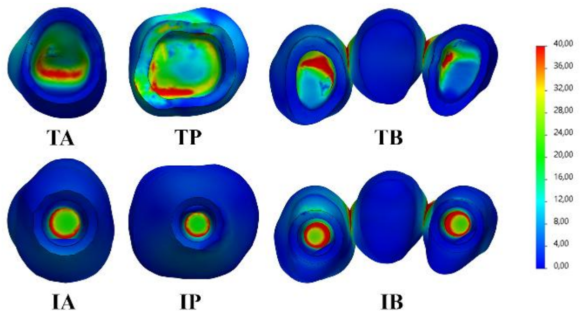

Figure 5. von Mises stress distributions on the inner surface of the models under oblique loading.

DISCUSSION

In the current treatment approach, it is important to select appropriate materials with high aesthetic and mechanical properties. In addition, monolithic restorations have been developed to avoid undesirable complication of zirconium-based restorations such as chipping.[20,21] In the current study, monolithic ZLS ceramics were preferred due to their mechanical and esthetic properties. It was reported that the monolithic ZLS is comparable to zirconium-based all-ceramic restorations and is suitable for use even in the posterior region.[5] However, there were few studies examining the effect of the difference in the milling and pressable forms of ZLS on the mechanical strength for ZLS FPDs. Main findings of this study revealed that there were no significant difference in the quantity and distribution of stresses between VITA Suprinity and VITA Ambria FPD models.

The von Mises stress was selected as a parameter to compare equivalant stress achieved in materials under occlusal loading. It is known that occlusal loads in adults' range between 400 and 800 N in right molar side, and the 500 N load determined for this study was widely used in similar FEA studies.[22,23]

Oblique loadings require more attention clinically due to create much stress on the prosthetic restorations than vertical and horizontal loadings. As a result of the study, von Mises stresses under oblique loading were found to be higher than those under vertical loading in all FPD models. Similarly, in many studies examining the effect of occlusal loading direction on mechanical response; it was shown that oblique loading affects the mechanical response and has higher stress and strain values compared to vertical loading.[24–26]

The results of this study also presented that von Mises stresses were higher in implant-supported FPDs compared to the tooth-supported form of the same FPD models. Biomechanical factors such as restoration and supporting types affect stress formation. The most important difference between tooth-supported and implant-supported restorations is that the osseointegrated dental implants do not have periodontal ligaments that provide shock absorption, and periodontal mechanoreceptors that provide tactile sensitivity and proprioceptive feedback. For this reason implant-supported FPDs are thought to be more sensitive to occlusal loading. Kayono and Esaki. reported that survival after 10 years of use was 89.2% for tooth-supported FPDs, while it was 86.7% for implant-supported FPDs.[27]

Our study demostrated that the highest von Mises stress values were detected in the IB-S and IB-A models under oblique loading. The reason why these FPDs have higher stress values than single-crown FPDs can be interpreted as the restoration length, flexibility, and bending on the pontic. Because the pontic in bridge restorations is an unsupported part and therefore causes stretching on connectors. The bending in the pontic creates tension forces on the retainers and increases the stress in the connector region. As a result of this study, the maximum stress in 3-unit FPDs (TB-S, TB-A, IB-S, and IB-A) were observed in the connectors, regardless of the supporting type. Similarly, Bataineh et al. investigated the effect of connector thickness on stress formation in LDS and zirconia all-ceramic 3-unit FPDs. As a result, they reported that regardless of the ceramic material and connector thickness, the stress in the restoration was concentrated in the connector regions and the amount of stress decreased inversely with the connector thickness.[28] As in similar studies, it is recommended to use an implant for each missing tooth to reduce the stress concentration on connectors and restoration components in 3-unit bridges.[29]

The stress distribution on the restoration in FEA studies provide insight into their survival in clinical use. Regarding the stress distribution on tooth-supported restorations, TP model was less than the TB model, but higher than the TA model. Therefore, in agree with the results of our study, Kassardjian et al, in their study comparing the success of anterior and posterior all-ceramic single-unit FPDs; reported that there were differences in failure rate between anterior (6.5%) and posterior (9.1%) all-ceramic restorations. It was also stated that although the difference is relatively small, it affects the all-ceramic material selection.[30]

In restored teeth, the stresses at the tooth-restoration and abutment-restoration interfaces are important. The continued stresses in this region may grow and propagate cracks, eventually fracture the restoration.[31] In this study, one of the areas where stress is highest in FPDs is the abutment-restoration and tooth-restoration interfaces. There are also studies stated that stress distribution under occlusal loading is primarily centered on the occlusal surface of the FPDs.[31,32] According to our results, it was noted that the maximum stress concentration in 3-unit FPD models were at connectors. In addition, similar to previous studies, in TB and IB models, it was found that the stresses on the inner surface of the restorations are concentrated close to the connectors.[31–33] Maximum stress occured in the mesial marginal edge on the inner surface of the second premolar crown and the distal marginal edge on the inner surface of the canine crown. The highest stress concentration at the occlusal surface was in the distal fossa of the pontic.

In the current study; it was observed that the inner surface, buccal surface and cervical finish line of the restorations were not affected from occlusal stresses. When compared to studies in which similar to our results; it may be emphasize that the highest stress value occurs in the functional cusps, and the lowest stress in the cervical line.[34] Previous FEA studies relating to the evaluation of stresses in multi-unit FPDs under occlusal loading also support our results.[32,33,35] Considering the results of this study, the stress distribution of FPDs was influenced by the type of restoration, direction of the force, and the number of units. Although, no significant difference was found between milling and pressable ZLS

FPDs in terms of the stress values on the restorations. Despite the importance of the findings of this study, it is important to consider that there are some limitations. FEA is a computer-assisted in vitro study in which it is not possible to exactly imitate oral conditions. Although there are material anisotropy, dynamic loadings and structural micro cracks in real, they are generally ignored in FEA in order to simplificate the models. Given the limitations of our study, long-term clinical studies are needed to confirm the results.

CONCLUSIONS

It was concluded that the stresses on the all-ceramic FPD models made with ZLS are affected by the direction of loading, the unit numbers of the FPD and supported by implant or prepared tooth. In all models, it was found that the stresses occurring under oblique loading were greater than the amount of stress occurring under vertical loading. The von Mises stresses on implant-supported models were higher than in tooth-supported models of the same FPDs. Similarly, the stresses in the 3-unit FPD were higher than the single-unit FPDs of the same support. However, no difference was found between VITA Suprinity PC and VITA Ambria at the same FPD in terms of stress concentration. Numerical stress values obtained for both ZLS ceramics were less than their maximum flexural strength

Ethics Committee Approval: This study does not require ethics committee approval as it involves publicly available data.
Informed Consent: This study does not require ethics committee approval because it contains publicly available data.
Peer-review: Externally peer-reviewed.
Author Contributions: Concept – Concept – M.B.; Design – M.B., S.D.; Supervision – S.D., A.A.; Resources – M.B.; Materials – M.B., S.D., H.B.; Data Collection and/or Processing – M.B., S.D., H.B.; Analysis and/or Interpretation – H.B.; Literature Search – M.B.; Manuscript Writing – M.B.; Critical Review – A.A.
Conflict of Interest: There is no conflict of interest. The authors do not have any financial interest in the companies whose materials are included in this article.
Financial Disclosure: The authors declared that this study received no financial support.
Etik Komite Onayı: Kamuya açık anonim veri setinin kullanımı nedeniyle Etik Kurul Onayı gerekli değildir.
Hasta Onamı: Kamuya açık anonim veri setinin kullanımı nedeniyle Bilgilendirilmiş Onam formuna gerek yoktur.
Hakem Değerlendirmesi: Dış bağımsız.
Yazar Katkıları: Fikir – M.B.; Tasarım - M.B., S.D.; Denetim - S.D., A.A.; Kaynaklar - M.B.; Malzemeler - M.B., S.D., H.B.; Veri Toplama ve/veya İşleme - M.B., S.D., H.B.; Analiz ve/veya Yorumlama - H.B.; Literatür Taraması - M.B.; El Yazması Yazımı - M.B.; Eleştirel İnceleme - A.A.
Çıkar Çatışması: Çıkar çatışması yoktur. Yazarların bu makalede yer alan materyallerin bulunduğu şirketlerle ilgili herhangi bir mali çıkarları yoktur.
Finansal Destek: Yazarlar bu çalışma için finansal destek almadığını beyan etmiştir.

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