ORIGINAL PAPER

EFFECT OF ONLAY MATERIAL AND PREPARATION DESIGN ON FATIGUE BEHAVIOR AND STRESS DISTRIBUTION IN MOLARS: 3D-FEA

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ABSTRACT

Introduction: Onlays are conservative restorations for posterior teeth that cover one cusp or more.

Objectives: The aim of this study was to evaluate fatigue behavior and stress distribution in mandibular molars with different onlays and preparation designs under static and cyclic conditions, using finite element analysis.

Material and methods: A model of a mandibular molar was obtained from a CBCT image. Mesio-occluso-distal cavities were presented with conservative and extensive buccolingual widths of the occlusal cavity. Buccal and lingual cusps were reduced. Therefore, onlays that covered buccal cusps and onlays that covered all cusps designs were obtained. All onlays were produced from three materials: lithium disilicate ceramic (LDS), polymer-infiltrated ceramic network (PICN), and zirconia ceramic. Safety factor was calculated and stress distribution was analyzed according to von Mises and maximum principal stress theories under static and cyclic conditions.

Results: Cyclic loading caused higher stresses than static loading. The safety factor of zirconia and LDS onlays was higher than 1, except for conservative preparation with all-cusp coverage. PICN showed the lowest values of safety factors and the highest stress concentration in the dental tissues, which was associated with the least stresses in onlays. LDS and zirconia ceramic onlays showed lower stress concentration in dental structures than PICN.

Conclusions: Loading conditions affected the results of stress in all models. Zirconia ceramic could be a suitable choice to restore mandibular molars, while PICN onlay might be an inappropriate restoration in terms of safety factors and stress distribution in restored dental structures.

Key words: fatigue, onlay, ceramics, polymers, finite element analysis.

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INTRODUCTION

Posterior teeth lose hard tissues frequently due to caries, tooth wear, or replacement of previous bad restorations [1]. When posterior teeth are to be restored, it is important to consider many factors, including quantity and quality of residual dental tissues, pulp vitality, and requirements of the restorative material [1]. Onlay, which is a partial coverage restoration that covers one cusp or more [2], is considered a conservative restorative choice for such teeth. It could be fabricated directly in the mouth, or indirectly in dental laboratory [3]. Although direct onlays are simple and more conservative, they might be difficult in applying in large cavities.

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Additionally, their mechanical properties tend to be weak when compared with indirect onlays. In contrast, indirect onlays provide more accurate proximal contact points and much better anatomical contour [4]. Gold was the standard material for indirect onlays because of its' high resistance to wear, but its' unnatural color is the main drawback of using it today. Moreover, the development of dental materials has allowed to produce tooth-colored restorative materials, such as dental ceramics [5].

Ceramic is an aesthetic material, which has high mechanical properties [5]. Many types and manufacturing methods of ceramic materials have been developed. Computer aided design/ computer aided manufacturing (CAD/CAM) is one of these methods. CAD/CAM technique controls the manufacturing process with precise parameters, which prevent the formation of defects in the body of restoration, while these defects cannot be avoided easily in using other manufacturing methods [6]. Numerous materials could be applied to fabricate indirect restorations, including onlays based on CAD/CAM technology [7]. Zirconia has been known by its' highest strength and toughness among dental ceramics (e.g., e.max ZirCAD, Ivoclar, Vivadent; Liechtenstein) [8]. According to yttria content, zirconia can contain 4% mol: 4Y-PSZ, or 5% mol: 5Y-PSZ (yttria partially stabilized zirconia), both of which show a large amount of isotropic cubic phase [7-9]. Lithium disilicate glass ceramic (LDS) (e.g., IPS e.max CAD, Ivoclar Vivadent; Liechtenstein) is made up of a glass phase and a crystalline phase. The crystalline phase consists of lithium disilicate crystals that form within the material during crystallization process. The fracture toughness and flexure strength of the material are doubled due to crystals size and their needle-like shape [10, 11]. A new category of ceramic, which consists of a ceramic matrix and a resin network, has been introduced. These materials can be machined easily by CAD/CAM technique, and their elastic moduli are close to elastic modulus of dentin. Polymer-infiltrated ceramic network (PICN) (e.g., Vita Enamic, Vita Zahnfabrik; Germany) is a sub-category of resin-matrix ceramic materials [12]. PICN, which is known as hybrid ceramic, is produced when a glass ceramic scaffold is infiltrated with polymers. Therefore, a 3-dimensional ceramic scaffold with regularly interconnected polymer particles, is formed [13].

Results of previous studies on the appropriate materials of onlays are still controversial. While a study found that the CAD/CAM material of onlay, including resin-matrix ceramic, did not affect the fracture resistance [14], some studies concluded that ceramic restorations were associated with better pattern of stress distribution and lower values of stress in dental tissues than composite resin restoration [7]. However, Ilgenstein *et al.* in 2015 found that resin-matrix ceramic onlays present better behavior compared with feldspathic ceramic onlays in terms of fracture strength [15]. Not only have the previous studies shown conflicting results regarding the restorative material, but also their results on onlay design were contrasting. Some authors found that restoration design did affect stress distribution [16, 17], whereas other researchers concluded that stress distribution was not influenced by design and dimension of the restoration [18]. Moreover, Ön Salman *et al.* did not find any significant difference between onlays that covered functional cusps and onlays, which covered all cusps in mandibular molars [14]. Another study concluded that ceramic onlay that covered all cusps was associated with lower stress compared with onlay covered with functional cusps in endodontically treated premolars [19].

Finite element analysis (FEA) is considered an effective means to evaluate stresses in complex structures, such as dental structures. Using FEA method, the clinical performance of restorative materials can be expected, as FEA allows to study the behavior of diverse restored structures under various circumstances [20-22].

Even though stress distribution in onlay-tooth complex has been studied, previous studies had not investigated the effect of fatigue loading on stress distribution in onlay-restored teeth. Moreover, the results of previous studies on onlay materials and preparation design are still conflicting. To our knowledge, the present investigation was one of the first studies to evaluate stresses in onlays and dental structures under both static and cyclic loadings.

OBJECTIVES

The aim of the current study was to evaluate the influence of static and dynamic conditions on fatigue behavior and stress distribution in mandibular molars with two preparation designs restored by different onlays, using finite element analysis.

MATERIAL AND METHODS

MODELING

This study was conducted using three-dimensional finite element analysis (3D-FEA), depending on a first mandibular molar model. A cone-beam computed tomographic (CBCT) image of a first mandibular molar was taken (Pax-i3D Green, Vatech, Gyeonggi-do; Seoul, South Korea). Then, the slices were imported to interactive medical image software. Mimics software and 3Matic software v. 21.0 (Materialise NV; Leuven, Belgium) were utilized to create 3D masks for dental structures, and create a 3D object of the periodontal ligament with 0.25 mm thickness. Using reverse engineering software (Geomagic Studio, Geomagic Inc.; USA), the objects were refined and converted into non-uniform rational basis spline (NURBS). After that, the models were converted into solid bodies in parasolid (x.t) file format using PowerShape Ultimate 2017 software (Autodesk Inc.; USA). Cortical and spongy bones were also represented

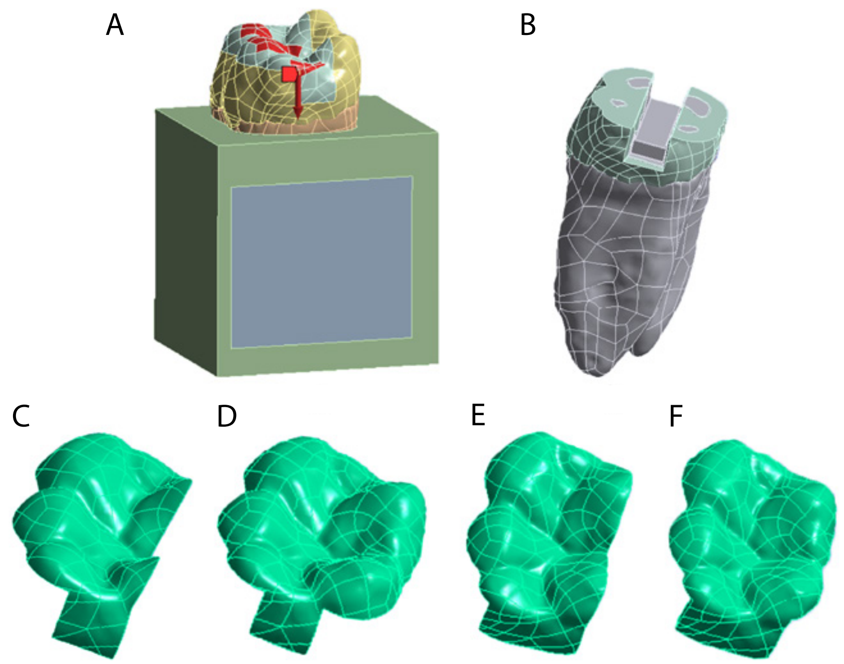

FIGURE 1. The model and onlays. **A)** Studied model and loading points. **B)** Prepared dental tissues. **C, D)** Conservative onlays that covered buccal cusps and all cusps, respectively. **E, F)** Extensive onlays that covered buccal cusps and all cusps, respectively

by creating solids using Solidworks 2018 software (Dassault Systèmes SolidWorks Corporation; USA). Boolean operations were performed with PowerShape Ultimate software to create restorations and prepare dental structures (Figure 1). After that, all models were exported as parasolid (x.t) files to perform FEA using Ansys Workbench v. 20.0 R2 software (Ansys Inc., Canonsburg; Pennsylvania, USA).

PREPARATION DESIGN

Preparation designs were created as described in literature [4]. A mesio-occluso-distal (MOD) cavity was created with 2.0 mm depth, 10-degree divergence of the internal walls, and 90-degree cavosurface margins (Figure 1). Buccal cusps were reduced by 1.5 mm in onlay models that covered buccal cusps only (B models). Lingual cusps were also reduced by 1 mm in onlay models that covered all cusps (A models) (Figure 1B) [4]. Two preparation widths, and conservative and extensive designs were created. The occlusal width of the cavity was one third of the buccolingual intercuspal distance for conservative preparation (1 models), and two thirds of the buccolingual intercuspal distance for extensive preparation (2 models). Then, onlays were created by three restorative materials: (L) lithium disilicate glass ceramic (LDS), (P) polymer-infiltrated ceramic network (PICN), and (Z) zirconia ceramic. Therefore, final models were as follows: 1BL, 2BL: conservative and extensive LDS onlay that covered buccal cusps, respectively; 1AL, 2AL: conservative and extensive LDS onlay that covered all cusps; 1BP, 2BP: conservative and extensive PICN onlay that covered buccal cusps, respectively; 1AP, 2AP: conservative and extensive PICN onlay that covered all cusps; 1BZ, 2BZ: conservative and extensive zirconia onlay that covered buccal cusps, respectively; 1AZ, 2AZ: conservative and extensive zirconia onlay that covered all cusps, respectively.

MATERIALS' PROPRIETIES AND MESHING

All materials were assumed to be isotropic, homogeneous, and linear elastic. Mechanical properties of all materials used in this study were taken from literature. A summary of the mechanical properties is shown in Table 1. S-N curves, which were utilized to evaluate fatigue life, represented alternating stress versus number of cycles. Fatigue life was evaluated based on Goodman's theory, given with the following formulas:

$$\sigma_m = \frac{(\sigma_{max} + \sigma_{min})}{2} \quad (1)$$

$$\sigma_a = \frac{(\sigma_{max} - \sigma_{min})}{2} \quad (2)$$

where σ_m is the mean stress, σ_a presents the alternating stress. The relationship between two stresses could be given as follows, according to the modified Goodman's theory:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_u} = \frac{1}{N_f} \quad (3)$$

TABLE 1. Physical properties of studied structures and materials

Material	Density (g/cm³)	Modulus of elasticity (GPa)	Poisson ratio	Tensile ultimate strength (MPa)	Compressive ultimate strength (MPa)	Reference
Enamel	2.8	84.0	0.33	11.5	384.0	[1, 7]
Dentin	2.0	18.6	0.30	105.5	297.0	[1, 7]
Pulp	–	0.002	0.45	0.05	2.9	[23, 24]
Periodontal ligament	1.1	0.069	0.45	2.4	29.5	[1, 25]
Cortical bone	1.3	13.7	0.30	130.0	200.0	[1, 26]
Spongy bone	1.3	1.4	0.30	8.0	50.0	[1, 26]
Lithium disilicate glass ceramic	2.47	83.5	0.21	173.0	448.0	[26, 27]
Polymer-infiltrated ceramic network	2.1-4.0	30.0	0.23	100.0	370.0	[7, 27]
Zirconia ceramic	–	210.0	0.24	745.0	904.0	[7]

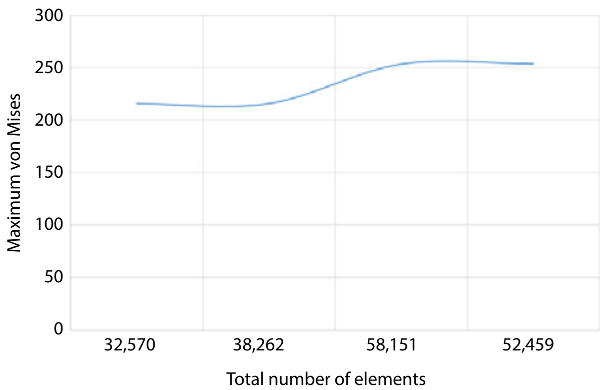

FIGURE 2. Mesh sensitivity

where S_e is the endurance limit, S_u is the ultimate tensile strength, and N_f is the safety factor in the loading cycle, provided with the following formula:

$$N_f = \frac{1}{\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_u}} \quad (4)$$

S-N curves of all structures were also taken from literature [9, 28-32]. S-N curves of the pulp and periodontal ligament were not found, and data of similar structures were applied. Then, a mesh of linear tetrahedral elements was generated for each model because of the complexity of geometry. The mesh was refined, and the total number of elements ranged between 48,451 and 61,844, while the number of nodes was about 86,759. Mesh sensitivity is shown in Figure 2.

BOUNDARY CONDITIONS

The models were fixed at the inferior surface of the cortical bone in all directions. An axial occlusal loading of 600 N was applied on buccal cusp tips, central fossa, and distal marginal ridge [1, 33, 34], as provided in Figure 1A.

The axial loading was parallel to the longitudinal axis of the tooth, representing a normal loading during the mastication cycle. Stresses were calculated according to von Mises theory and maximum principal stress theory to evaluate stress distribution in all models. A fatigue analysis was also performed based on S-N curves of all components of the models. A loading of 600 N was applied statically under static condition, while dynamic loading under fatigue condition increased gradually by 75 N until it reached 600 N during 240 milli seconds. This duration was a part of the mastication cycle during which, the teeth were subjected to occlusal forces [35].

RESULTS

Visual maps of stress distribution and values of von Mises and maximum principal stresses are shown in Figures 3-10. Red colors in visual maps refer to the highest stress concentration, while blue color refers to the least stress concentration. Safety factors of enamel, dentin, and onlay in all models are presented in Table 2.

VON MISES AND MAXIMUM PRINCIPAL STRESSES

Distribution patterns of von Mises stress and maximum principal stress were similar, with less concentration in maximum principal stress. Von Mises stress concentrated in the cervical region and the distal surface of the coronal part of the tooth in all the models under both loading conditions (Figure 3). Stress concentration was also seen in the loading points in onlays: in the buccal cusps and the distal marginal ridge when static and dynamic loadings were applied (Figures 3 and 4). Maximum principal (tensile) stress concentrated in the distal marginal ridge in onlays, whatever the loading condition, preparation design, and coverage of cusps were situated (Figures 5 and 6). Furthermore, tensile stress concentration under cyclic loading was seen in the reduced

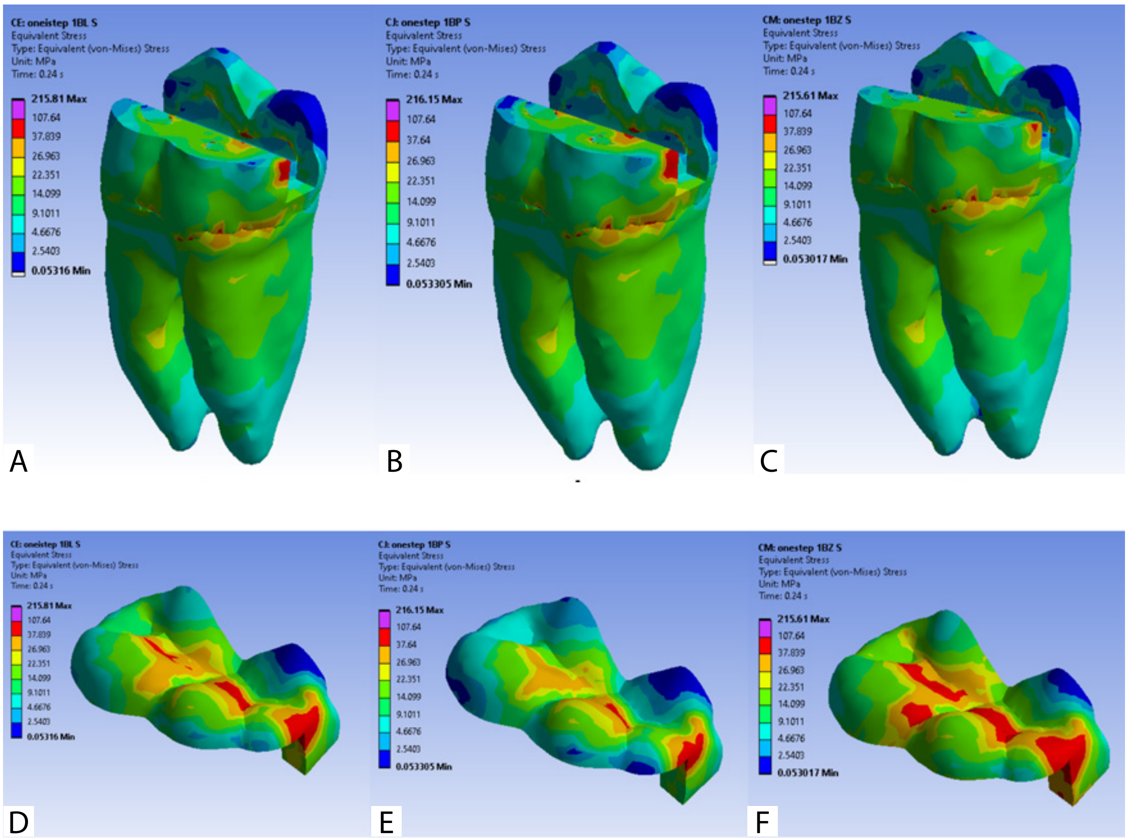

FIGURE 3. Von Mises stress distribution in 1B models (conservative preparation with covering buccal cusps) under static loading. **A, D**) LDS model; **B, E**) PICN model; **C, F**) Zirconia model; **A-C**) Stress distribution in dental tissues; **D-F**) Stress distribution in onlays

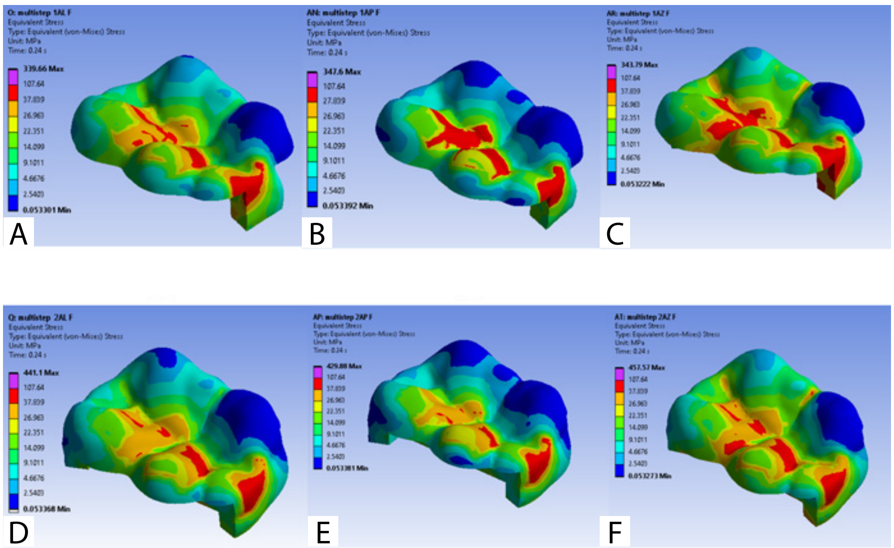

FIGURE 4. Von Mises stress distribution in onlays that covered all cusps under cyclic loading. **A, D**) LDS onlay; **B, E**) PICN onlay; **C, F**) Zirconia onlay; **A-C**) Onlays in conservative preparation models; **D-F**) Onlays in extensive preparation models

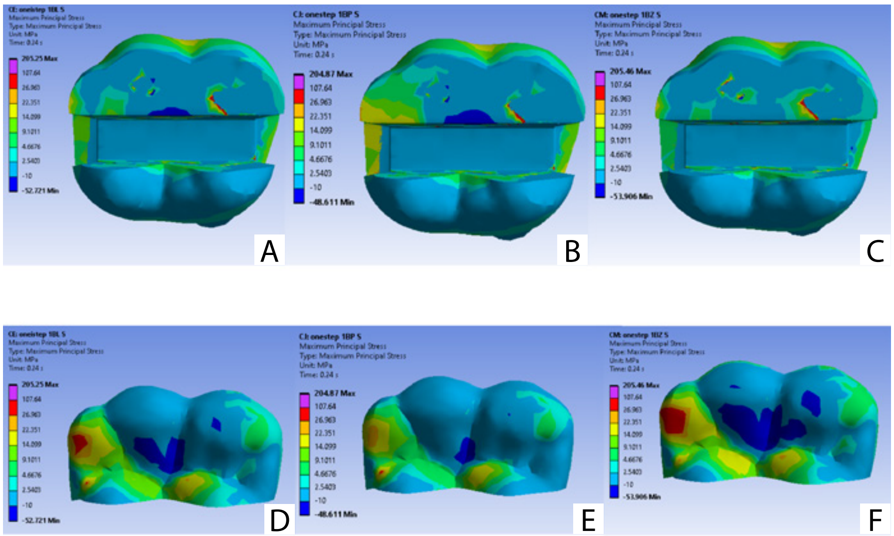

FIGURE 5. Maximum principal stress distribution in 1B models (conservative preparation with covering buccal cusps) under static loading. **A, D**) LDS model; **B, E**) PICN model; **C, F**) Zirconia model; **A-C**) Stress distribution in dental tissues; **D-F**) Stress distribution in onlays

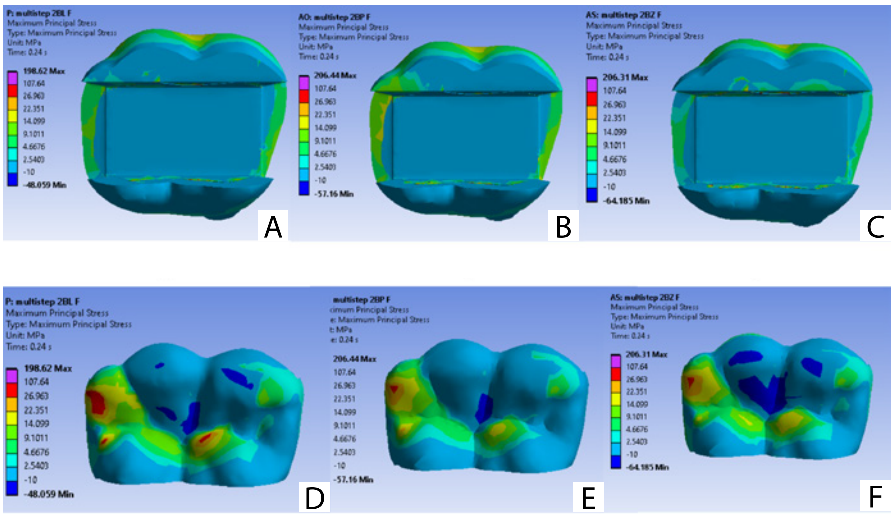

FIGURE 6. Maximum principal stress in 2B models (extensive preparation with covering buccal cusps) under cyclic loading. **A, D**) LDS model; **B, E**) PICN model; **C, F**) Zirconia model; **A-C**) Stress distribution in dental tissues; **D-F**) Stress distribution in onlays

buccal cusps in 1B models and in all reduced cusps in 1A models (Figure 5).

Cyclic loading showed higher stress concentration in onlays and dental structures compared with static loading (Figure 7). Although the cyclic loading increased the values of von Mises stress in onlays by about 40%, and the values of tensile stress by 40-50%, it caused a slightly greater values of von Mises and tensile stresses in the enamel and dentin compared with the static loading (Figures 8 and 9).

According to the onlay material, PICN showed the highest stress concentration in the dental tissues (Figure 7) and the least stresses in onlays among the studied materials under both loading circumstances (Figures 3 and 5). On the contrary, zirconia onlays were associated with the least stress concentration in the dental tissues and the greatest stress concentration within the onlay (Figures 3 and 5). Zirconia and lithium disilicate (LDS) ceramic onlays showed similar values of stresses, both

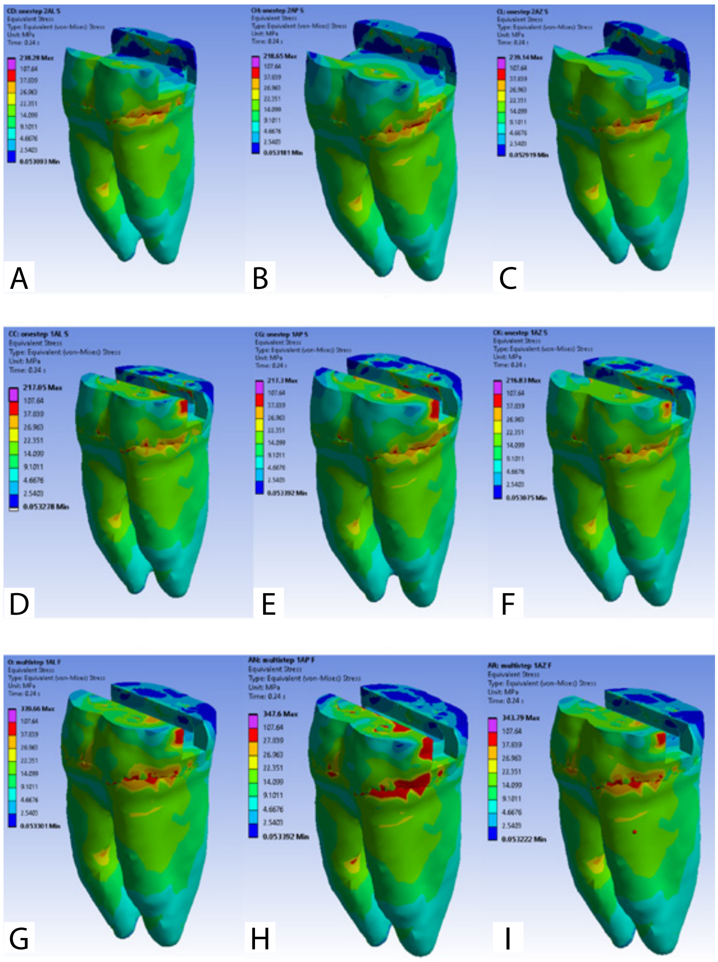

FIGURE 7. Von Mises stress distribution in dental tissues in 1A and 2A models (with covering all cusps). **A, D, G**) Dental structures restored in LDS model; **B, E, H**) Dental structures restored in PICN model; C, F) Dental structures restored in zirconia model; **A, B, C, I**) Stress distribution under static loading; **A-C**) Stress distribution in dental tissues in extensive preparation models under static loading; **D-F**) Stress distribution in dental tissues in conservative preparation models under static loading; **G-I**) Stress distribution in dental tissues in conservative preparation models under cyclic loading

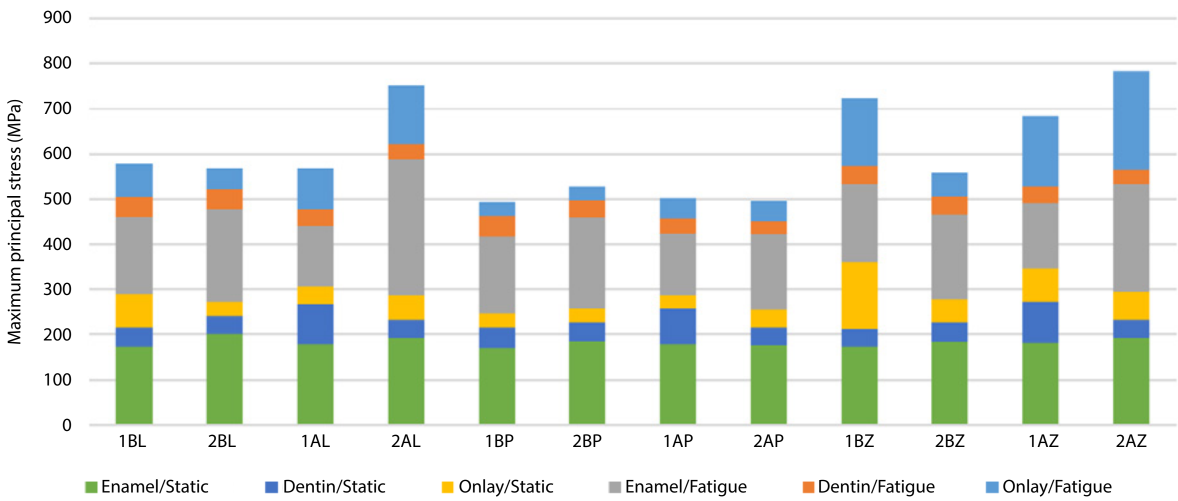

FIGURE 8. Maximum principal stress values in enamel, dentin, and onlay under static and dynamic loadings

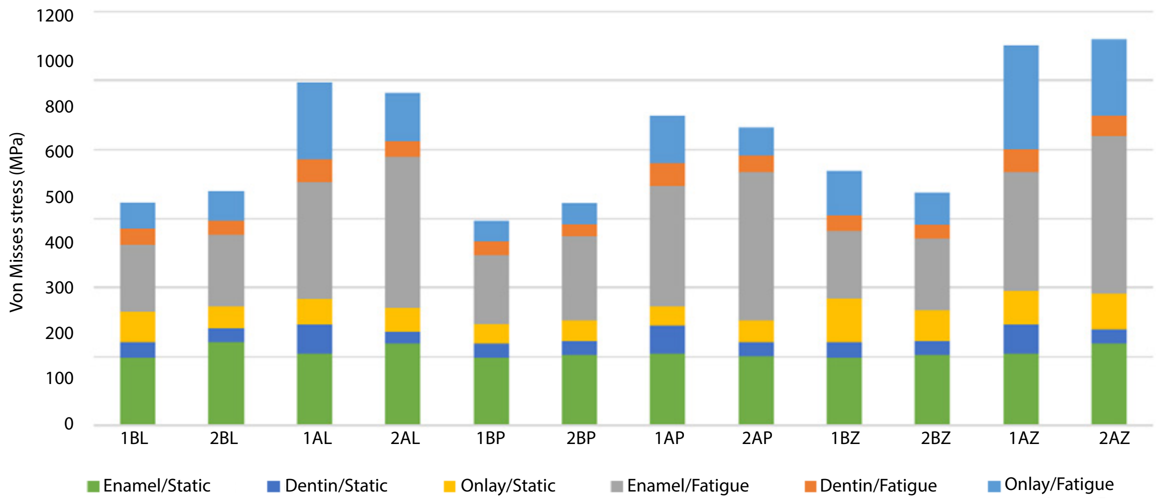

FIGURE 9. Von Mises stress values in enamel, dentin, and onlay under static and dynamic loadings

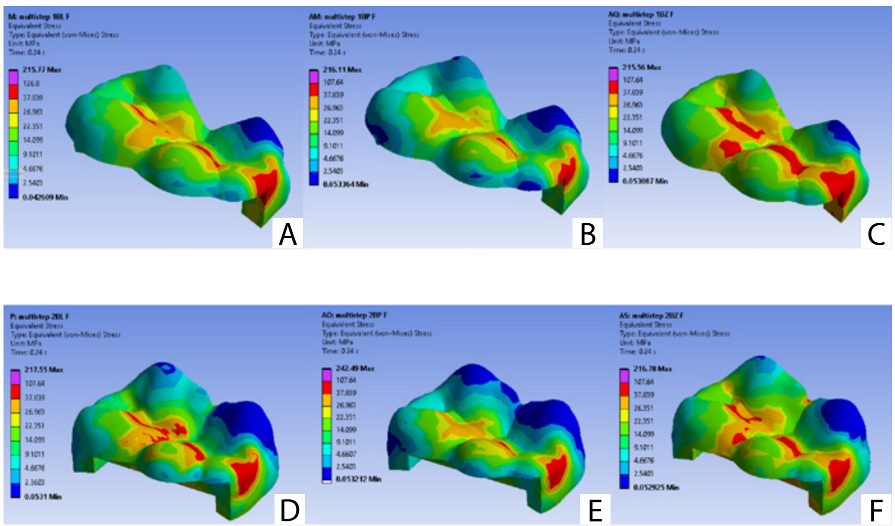

FIGURE 10. Von Mises stress distribution in onlays that covered buccal cusps under cyclic loading. **A, D)** LDS onlay; **B, E)** PICN onlay; **C, F)** Zirconia onlay; **A-C)** Onlays in conservative preparation models; **D-F)** Onlays in extensive preparation models

of which were associated with higher stress values than stresses in PICN models (Figures 8 and 9).

Under dynamic loading and regarding preparation width, onlays that covered all cusps were associated with greater von Mises stress concentration, when the preparation was conservative (Figure 3). In contrast, stresses were higher in extensive preparation models, which were restored with onlays that covered buccal cusps (Figure 10). Moreover, the cyclic loading was associated with higher tensile stress in all-cusp coverage models, whatever the width of the preparation was. It also caused greater values of tensile stress in conservative preparation than extensive preparation (Figures 8 and 9). However, static condition showed higher stress concentration in onlays with less stress concentration in dental structures in extensive preparation models than conservative preparation models, whatever the design of the onlay was (Figures 7A-7F). In addition, von Mises stress distribution was similar in onlays that covered all cusps and onlays that covered buccal cusps, when the static loading was applied.

SAFETY FACTORS

Although the safety factor was higher than 1 in zirconia and LDS onlays (except for 1AL, 2AL, and 1AZ models), it was less than 1 in all PICN onlays, whatever the design of the preparation was (Table 2). The safety factor of the dentin was the lowest when all cusps were covered by the onlay in conservative preparation models (1AL, 1AP, and 1AZ models) (Table 2).

DISCUSSION

Restoration of posterior teeth is still a challenge in daily clinical practice. Onlays from several materials offer conservative alternatives for the restoration of such teeth [7]. However, findings of previous studies on the best preparation design and materials of onlays are still conflicting [7, 14-19]. Being used effectively as a research tool, finite element analysis (FEA) has allowed researchers to determine stress distribution in complex structures, including tooth-restoration complex [11]. It also provides a non-destructive method to study fatigue life and predict fatigue behavior of complex structures in contrast to conventional tests and clinical trials, which are time-consuming [20]. Reviewing the medical literature, it was found that fatigue life had been investigated using 3D numerical analysis in dental implants [30], intra-radicular posts [20], and in composite resin inlays [36], without being studied in onlay-restored teeth.

Not only do posterior teeth lose hard tissues repeatedly, but they are also subjected to functional and parafunctional forces of various directions and magnitudes [1, 22]. Therefore in this study, mandibular molar models with MOD cavities were used to evaluate the influence of preparation design and onlay material on stress distribution and fatigue behavior of onlay-tooth complex under static and cyclic conditions. An average axial force of 600 N was applied on the occlusal contact points [1, 33, 34]. The axial loading was applied to stimulate the normal force on mandibular molars. As mentioned in the literature, periodontal tissues were represented to minimize the effect of necessary simplification procedures [17]. The cement layer was not considered in the present study, as it was assumed to be a part of dental structures. Furthermore, its' thickness was too thin to be perfectly created in the models [21, 37]. Equivalent von Mises stress is the combination of tensile, compressive, and shear stresses in the entire stress field. Since von Mises criteria represent the overall stress situation, they are considered indicators of the possible failure and its' location [17, 20, 21, 38]. Maximum principal stress theory that refers to tensile stress is considered as an acceptable index of failure for brittle materials, including dental ceramics [21]. Thus, von Mises stress and maximum principal stress theories were utilized in this study to determine stresses in the models. Fatigue life and safety factor were also investigated. Safety factor could be calculated from the ratio between the strength of a component and the maximum von Mises stress in that component. The greater the safety factor, the less susceptible to failure the structure. This means that the structure could withstand more stresses before failure when its' safety factor is equal or above 1, while crucial values of safety factor (below 1) indicate that the structure tends to fail rapidly under stresses [20, 30].

Cyclic loading caused higher values of stresses and greater stress concentration in the components of all models compared with static loading. This result is compatible with finding of an earlier study, which concluded that maximum stresses in implants and surrounding bone under fatigue loading were higher than those caused by static loading [30]. It also corresponds to the fact of the fatigue phenomenon. Fatigue is known as the localized damage in a material that is subjected to cyclic loading [20]. Consequently, failure would occur in the material due to fatigue after years of functioning [39].

TABLE 2. Minimum safety factor in dental tissues and onlays

Model	Enamel	Dentin	Onlay
1BL	5.0828	0.67212	1.1795
2BL	4.823	0.7849	1.0278
1AL	2.9441	0.46597	0.40243
2AL	2.267	0.66617	0.64609
1BP	5.1125	0.7189	0.6789
2BP	4.1239	0.80442	0.66028
1AP	2.8769	0.45203	0.28927
2AP	2.3262	0.60465	0.49295
1BZ	5.0869	0.67628	1.963
2BZ	4.8552	0.7902	2.6795
1AZ	2.9087	0.46426	0.82674
2AZ	2.1854	0.50231	1.1379

Visual maps showed that von Mises and tensile stress concentration increased in onlays, while it decreased in dental structures in the extensive preparation models compared with the conservative preparation models under static loading. This could be attributed to the width of restoration. Increasing the width of the restoration was associated with high stresses concentrated within it. This finding may indicate that cracks could occur in the restoration, and this might protect residual dental tissues [40].

The results showed that von Mises stress was concentrated in the cervical region of the tooth as well as in the loading points in onlays. These findings are in line with previous studies [1, 33]. Visual maps also showed that maximum principal (tensile) stress was concentrated in the distal marginal ridge in onlays. Tensile stress in onlays caused by the occlusal force could be the primary reason for material failure, even though other aspects might influence the failure risk of restorative material, such as its' mechanical properties [18].

According to the restorative material and regardless of the preparation design, opposed to zirconia and LDS onlays, PICN onlays showed the greatest stress concentration in the dental tissues and the least stresses in the restoration. PICN onlays also showed the lowest values of the safety factor. These crucial values of the safety factor of PICN restorations make it very important to be careful when planning restoration of molars with PICN onlays. The pattern of stress distribution might be attributed to the elastic moduli of restorative materials [11, 16, 38]. Stiff materials with high elastic moduli tend to concentrate stresses within them, instead of transferring stresses to surrounding structures [38]. Therefore, they could protect dental structures since cracks might appear in the material rather than in the tooth. This could explain the results of a previous study, which found that fractures had occurred in the ceramic onlays before the fracture of dental structures [38].

Taking into account the ultimate tensile strength and endurance (fatigue) limit of the restorative materials, maximum principal stresses in onlays were lower than ultimate tensile stress of their materials in all models. Nonetheless, the maximum von Mises stresses in zirconia onlays were lower than the endurance limit of zirconia ceramic, except when the onlay covered all cusps in conservative model. On the other hand, stresses in LDS onlays that covered all cusps were higher than the endurance limit of LDS, whatever the preparation width was (1AL and 2AL models). Furthermore, the maximum stresses in all PICN onlay models were higher than the endurance limit of restorative material. These findings, which are in agreement with the results of the safety factor, could predict that zirconia ceramic might be the best material to tolerate stresses before failure occurs.

Regarding the coverage of cusps, the maximum principal stress in onlays was higher in models with covering all cusps, whatever the preparation width was. This could be explained by the design of the onlay. Onlays that covered all cusps received all of the occlusal loading, which caused higher stresses in the restoration. Therefore, onlays, which cover all cusps might provide better protection of dental tissues. However, visual maps showed similar patterns of von Mises stress distribution in the models of onlays that covered functional cusps and onlays that covered all cusps. In spite of this similarity under the static condition, the dynamic loading did affect the behavior of restorations and the pattern of stress distribution. This could suggest that cyclic loadings can represent the reality much better than applying static conditions. Fatigue loading caused lower stresses in conservative preparation models with onlays that covered buccal cusps (1B models), when compared with onlays that covered all cusps (1A models). On the contrary, extensive preparation models restored with onlays that covered buccal cusps (2B models) showed higher stresses than models restored by onlays that covered all cusps (2A models). This finding is compatible with the results of the safety factor, which increased in the models of onlays that covered all cusps with extensive preparation design (2A models). The low safety factor of dentin in 1AL, 1AP, and 1AZ models may indicate that covering all cusps might not be recommended if the preparation width does not exceed one third of the buccolingual inter-cuspal distance.

It is important to mention that potential failure in onlay-tooth complex is difficult to be expected as it does not only depend on the elastic moduli of the restorative materials and their safety factors, but many other factors can also affect the type of failure and its' location, including thermal expansion coefficients of restorative materials and various biomechanical factors in oral environment. Moreover, S-N curves, which are essential for fatigue analysis, are not easily available for all structures and restorative materials. Therefore, more *in-vitro* studies on various restorative materials and structures are strongly recommended to obtain necessary data.

CONCLUSIONS

Within the limitations of this study, we can conclude that cyclic loading caused higher stresses with different results, according to the design of the onlay and the preparation, compared with static loading. Moreover, the high safety factor of zirconia onlays could make zirconia ceramic the best material for onlays to withstand stresses in the oral environment. On the contrary, PICN may be an unsuitable material for onlays, as it showed the lowest safety factor and the worst pattern of stress distribution in dental tissues. To ensure high safety factor and proper distribution of stresses in onlay-tooth complex, it might be better to cover all cusps when the buccolingual width of the preparation is increased. Furthermore, covering buccal cusps only in conservative cavities might be better in terms of stress distribution and safety factor under dynamic loadings.

CONFLICT OF INTEREST

The authors declare no potential conflict of interests with respect to the authorship and/ or publication of this article.

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