Influence of occlusal contact and cusp inclination on the biomechanical character of a maxillary premolar: A finite element analysis

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Statement of problem. Restoring teeth with large amounts of dentin loss is challenging, especially for posterior teeth with high cusps. However, strategies for reducing the lateral forces are based on clinical experience instead of than scientific evidence.

Purpose. The purpose of this study was to analyze the biomechanical characteristics of maxillary premolars with different ferrule configurations and to investigate the influence of occlusal contact and cusp inclination on stress distribution with the finite element method.

Material and methods. Five numerical casts of a maxillary premolar were generated; each adopted 1 of the 5 coronal dentin configurations: i (access cavity with 4-mm dentin height) and ii to v (2-mm complete ferrule, 2-mm facial ferrule, 2-mm palatal ferrule, 2-mm proximal ferrule, and restored with a post and core, respectively). Both gold-alloy and glass-fiber posts were modeled. An oblique load of 200 N was applied to the top, middle, and bottom of the 45-degree facial cusps. The cusp inclination was remodeled to 60 degrees, followed by the application of a 200-N load to the top. The values of the maximum principal stress and von Mises stress were calculated to assess overload risk.

Results. When the top of 45-degree facial cusps was loaded, the maximum local stress concentration on dentin was found in teeth with a facial ferrule and restored with a gold-alloy post. When the middle of 45-degree facial cusps were loaded, the principal stresses of teeth with a complete ferrule, palatal ferrule, and proximal ferrule were similar to those of the access cavity teeth. In contrast, the principal stress of a tooth with a facial ferrule was close to that of the access cavity tooth after remodeling the facial inclination to 60 degrees.

Conclusions. Maxillary premolars with only facial dentin remaining show higher local stress on root dentin. Altering the loading position and reducing the facial cusp inclination can reduce local stresses. (J Prosthet Dent 2014;112:1238-1245)

Clinical Implications

Numerical calculations indicate that the ability of post-and-core restored teeth to withstand occlusal forces may be inferior to that of vital teeth. For a maxillary premolar with extensive defects, a risk of overloading arises when it bears an oblique load; appropriate occlusal design would improve biomechanical behavior and greatly reduce this risk.

The restoration of endodontically treated teeth is challenging when a large amount of dentin has been lost. The longevity of these teeth depends mainly on the remaining hard dental tissue. The ability of the restoration with a ferrule to bind the remaining tooth structure together is believed to be the key to long-term stability and is essential for a post-and-core restoration.[1] In vitro studies have found that 1.5- to 2-mm ferrule height is ideal[1-3]

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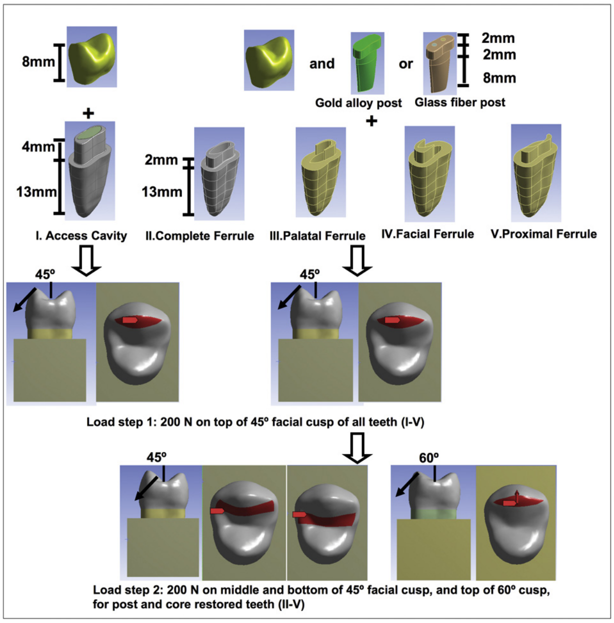


1 Maxillary premolars with different coronal dentin configurations and loading protocols.

and check that the resistance of reconstructed teeth is directly related to the amount of remaining sound hard tooth.[4,5] Both the amount of tooth structure loss and the position of coronal defects are associated with the loading resistance of the teeth. The results of proximal caries, trauma, or occlusal overload often make it difficult to achieve a complete "all around" dental ferrule. A nonuniform ferrule may have a negative influence on the fracture resistance of post-and-core restored teeth, although this is still superior to the nonferrule scenario.[6,7] According to some in vitro studies, the location of sound tooth structure that provides resistance to occlusal forces is probably more important than having circumferential axial wall dentin.[6-8]

When limited coronal dentin remains so that a standard ferrule is not possible, the risk of tooth fracture and restoration debonding is much higher.[5-7,9,10] In group function situations, this is worse for maxillary premolars, which, because of their high cusps, are exposed to repeated oblique occlusion forces that are translated into high lateral forces.[11] Therefore, when prosthetic treatment is planned for such teeth, attention should be focused on protecting the damaged teeth from high functional loads to avoid failures. Results of a number of studies indicate that the occlusal design should be modified for teeth with substantial dentin loss to protect the supporting units and the restoration from overload.[12] Researchers recommend minimizing the lateral forces to reduce the risk of fatigue fracture.[13] However, the way in which lateral forces should be reduced and the extent of this reduction remains to be determined.

Therefore, the purpose of this study was to analyze, by means of 3-dimensional (3D) linear-elasticity finite element simulations, the biomechanical character and dentin fracture risk of 4 post-and-core–restored maxillary premolars with either complete or partial ferrules. To investigate the influence of occlusal contact position on stress distribution in dentin, 3D casts were designed with different loading positions on the facial cusps to simulate the occlusal adjustment procedure that would be carried out clinically. The influence of facial cusp inclination also was examined.

MATERIAL AND METHODS

The geometry of a maxillary premolar was obtained by scanning an acrylic resin tooth replica. The 3D cast was reconstructed by using modeling software (UG NX 6.0; Ansys). Five 3D casts were created based on this initial cast to simulate maxillary premolars with different coronal dentin configurations (Fig. 1, Table I) as follows: i, pulpless tooth with access cavity and

Table I. Geometric properties and load steps of 5 teeth analyzed

Group	Crown Height (mm)	Root Length (mm)	Coronal Dentin Height (mm)	Post Length (mm): Above the Ferrule (h_1)	Post Length (mm): In the Root (h_2)	Load Steps: 45-Degree Cusp Top	Load Steps: 45-Degree Cusp Middle	Load Steps: 45-Degree Cusp Bottom	Load Steps: 60-Degree Cusp Bottom
Access cavity	8	13	4	–	–	√	–	–	–
Complete ferrule	8	13	2	2	10	√	√	√	√
Palatal ferrule	8	13	2	2	10	√	√	√	√
Facial ferrule	8	13	2	2	10	√	√	√	√
Proximal ferrule	8	13	2	2	10	√	√	√	√

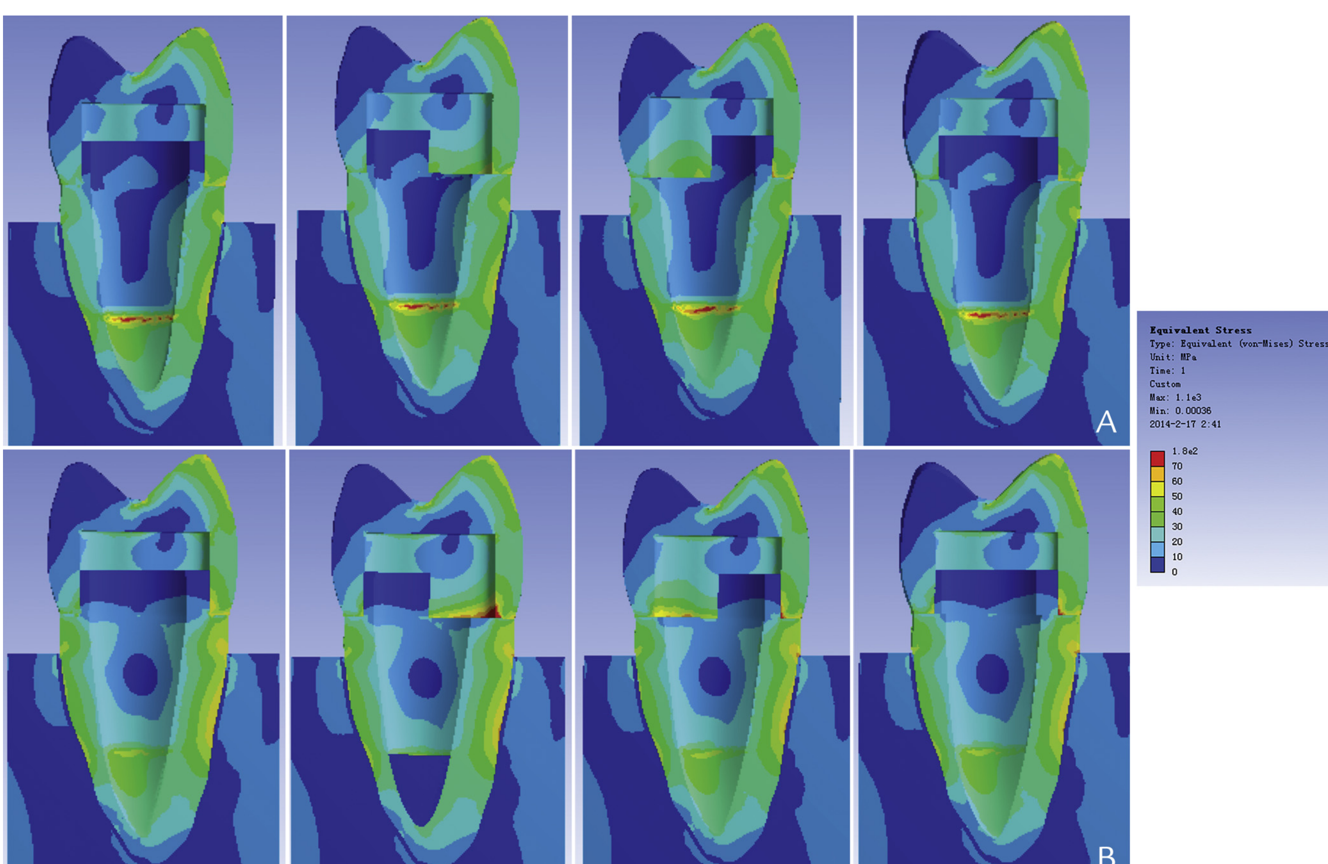
TABLE II. Material properties

Materials	Young Modulus (E) (GPa)	Poisson Ratio (ν)	Reference No.
Dentin	18.6	0.31	18
Crown (ceramic)	380	0.25	18
Gold-alloy post	93.0	0.33	18
Glass-fiber post	40.0/11.0	0.26/0.32	18
Core composite resin	6.9E-4	0.30	19
Gutta percha	0.14	0.40	14
Cortical bone	13.7	0.30	20
Trabecular bone	1.37	0.30	20
Periodontal ligament	6.89E-5	0. 45	21

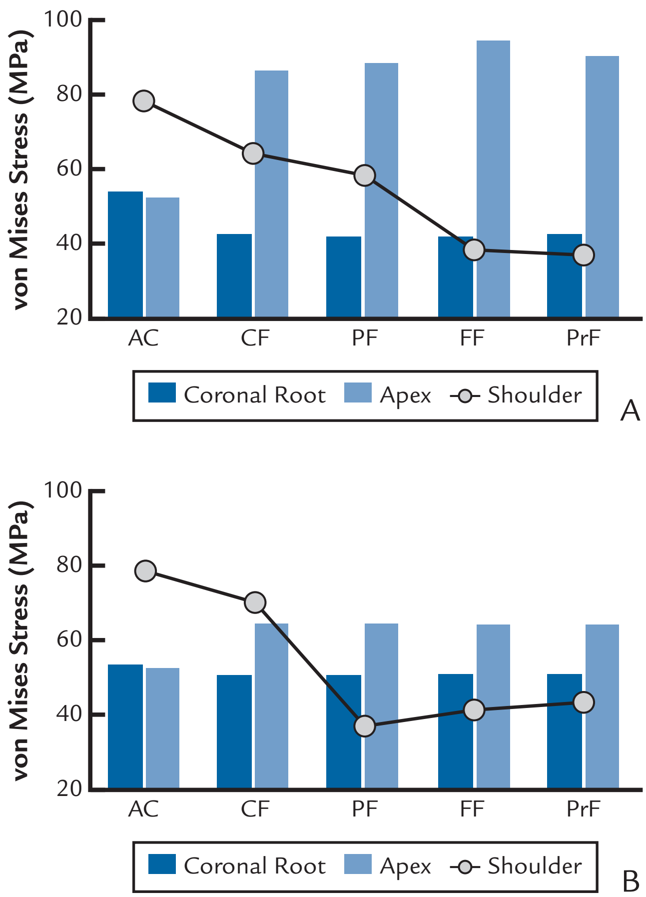
4 mm remaining coronal dentin (AC); ii, pulpless tooth with 2-mm complete ferrule (360 degree) (CF); iii, pulpless tooth with 2-mm palatal ferrule (180-degree) (PaF); iv, pulpless tooth with 2-mm facial ferrule (180-degree) (FF); and v, pulpless tooth with 2-mm proximal ferrule (180-degree) (PrF). All the casts were developed with 0.2-mm periodontal ligament and bone block. The AC cast tooth was restored with a single complete crown, and the others, ii to v, were restored with a post and core and a complete crown. Modeled posts consisted of gold alloy or glass fiber and were assumed to be perfectly bonded to the root dentin. The complete crown was ceramic, with a 45-degree facial cusp inclination.

The 3D casts were imported into a finite element software package (ANSYA Workbench 10.0; Ansys). All the materials were presumed to be linearly elastic, homogeneous, and isotropic, except for the glass-fiber posts, which were modeled as transversally isotropic (Table II). Three-dimensional meshes were created through 10-node tetrahedral elements with quadratic displacement shape functions and 3 degrees of freedom per node. The mean mesh size was approximately 0.2 mm, and the bottom section of the bone block was assumed to be fixed. The casts included approximately 210 000 elements and 290 000 nodes.

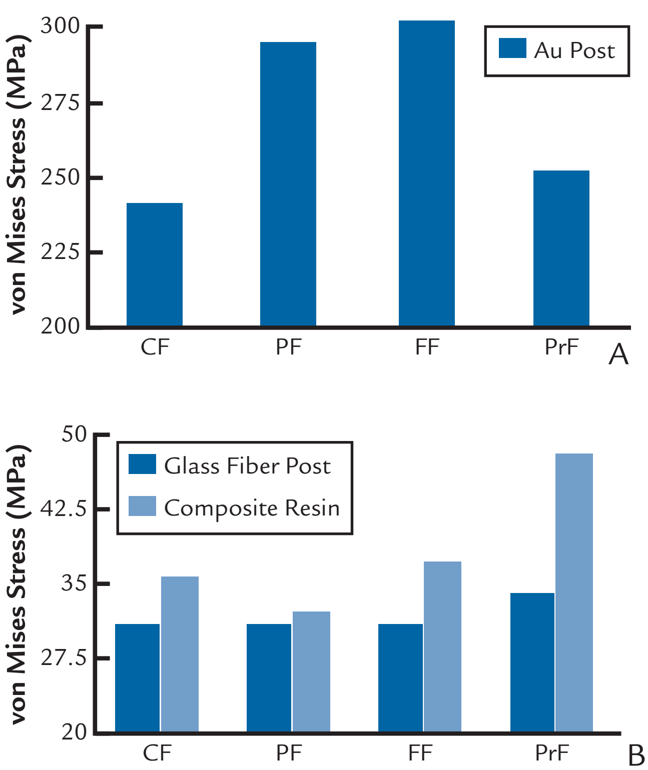
To evaluate the influence of occlusal contact and cusp inclination on tooth behavior, 2 load steps were separately processed. First, a 200-N oblique static load was applied to all the teeth (i-v). The load was angled at 45 degrees with respect to the occlusal plane and applied to the top of the facial cusps.



2 Von Mises stress contours of teeth with different ferrules. A, Gold-alloy-post restored teeth. B, Glass-fiber-post restored teeth.



3 Von Mises stress measured at shoulder, crown, and apex of teeth. A, Gold-alloy-post restored teeth. B, Glass-fiber-post restored teeth.



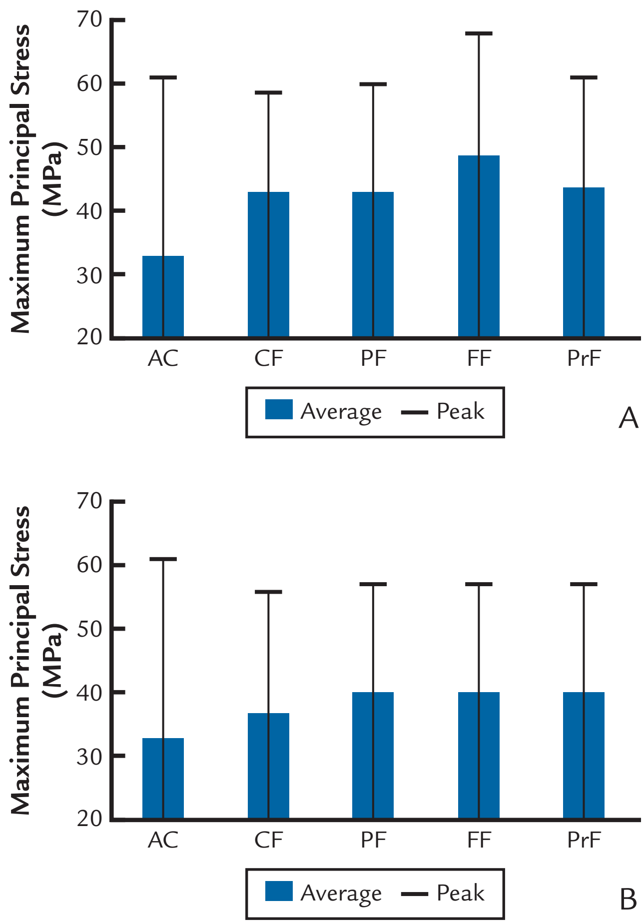
4 Von Mises stress measured at post and core. A, Gold-alloy-post. B, Glass-fiber-post and composite resin.

Second, for the post-and-core restored teeth (ii-v), the same 200-N load was applied to the middle and bottom of the facial cusps. After that, the facial cusp inclination of the complete crown was remodeled from 45 to 60 degrees, with the 200-N load applied to the top of a 60 degrees facial cusp (Fig. 1, Table I). The resulting stress fields of the post-and-core restored teeth were compared with that of the complete crown restored tooth (AC). The peak values of von Mises stress (σ_{vM}) and maximal principal stress (σ_{max}) were used to quantify the local risk of fracture at the dentin. The interface of the dentin and restoration were analyzed to determine the potential for bonding failure.

RESULTS

The von Mises stress distributions were computed for the 4 premolars restored with either a gold-alloy or a glass-fiber post, and the results are reported in Figures 2, 3, which graphically compare the von Mises values at the shoulder, the coronal root, and the apex for all test configurations. The AC tooth induced the highest von Mises stress at the shoulder (approximately 78 MPa). Stress concentration was located at the apex of the gold-alloy restored teeth, and the highest von Mises stress was observed in the FF tooth (approximately 94 MPa). When the glass-fiber restored teeth were analyzed, the stress values at the apex were lower than those of the gold-alloy restored teeth. The von Mises stress induced at the shoulder of the CF tooth (approximately 70 MPa) was greater than that for the other 3 glass-fiber restored teeth. The von Mises stresses measured for post-and-core materials are presented in Figure 4. The FF tooth induced the highest stress in the gold-alloy post, approximately 374 MPa. The stress values in the glass-fiber post were approximately 31 to 34 MPa, whereas the stresses at the composite resin ranged from 32 MPa (PF) to 48 MPa (PrF).

A comparison of the peak and average values of the maximal principal



5 Maximal principal stress measured at dentin. A, Gold-alloy-post restored teeth. B, Glass-fiber-post restored teeth.

stress measured at the dentin of all test teeth is presented in Figure 5. The peak and the average maximal principal stress of the AC tooth were approximately 61 MPa and 33 MPa. The peak stresses induced by the gold-alloy post restored teeth ranged from 59 MPa (CF) to 68 MPa (FF). Average stress values ranged from 43 MPa (PF) to 49 MPa (FF) in gold-alloy restored teeth; approximately 24% to 33% higher than the AC tooth. With a glass-fiber post, the peak maximal principal stresses were approximately 57 MPa, 7% lower than the AC tooth. Average stress values ranged from 37 MPa (CF) to 40 MPa (PF, FF, PrF), approximately 11% to 18% higher than that for the AC tooth. The maximal principal stress distributions at the dentin under different loading patterns are presented in Figure 6. Compared with loading on the top of a 45-degree facial cusp, stress was reduced for the gold-alloy and glass-fiber post restorations when the middle or bottom was loaded and the cusp inclination was reduced.

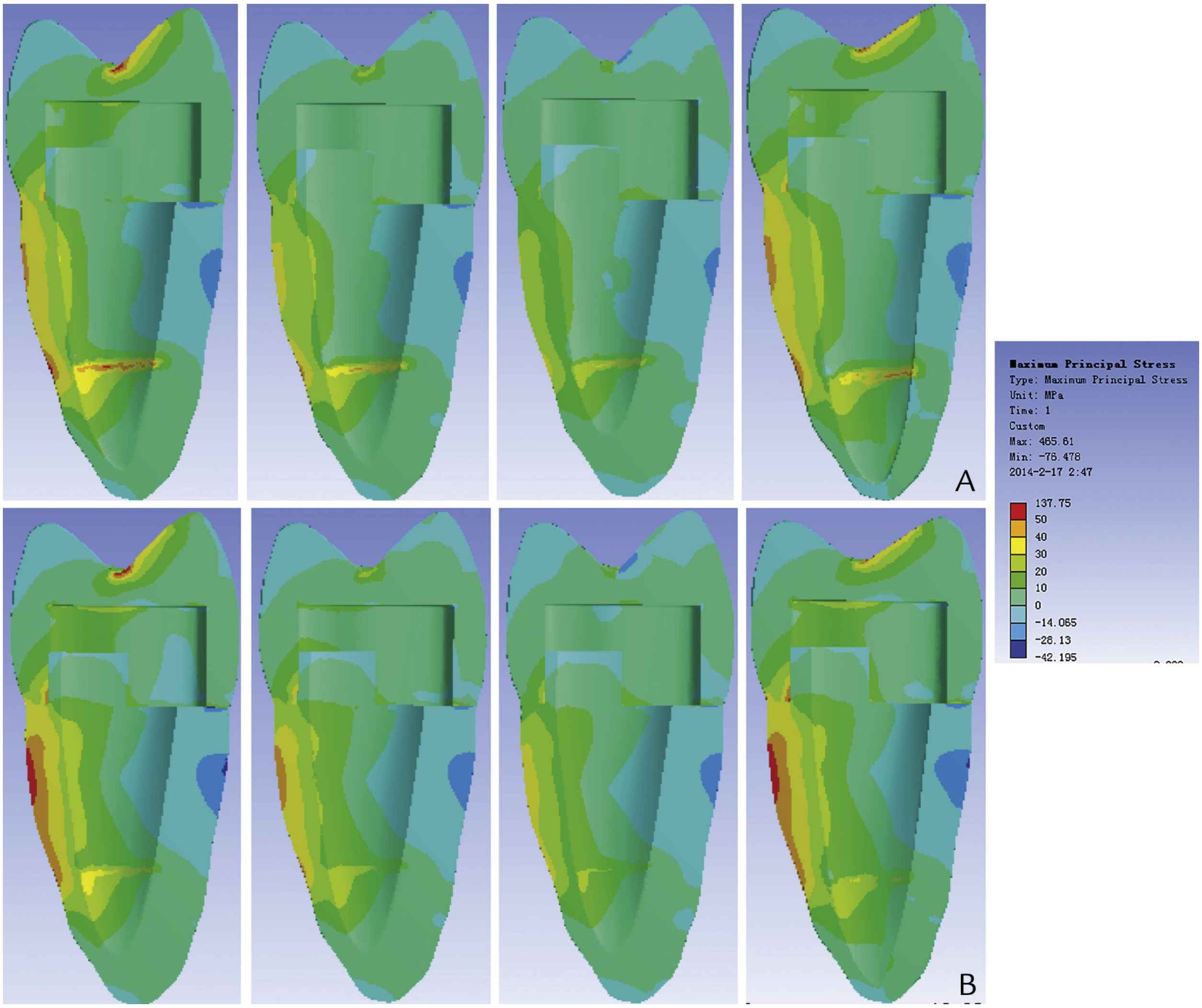
The peak and average values of principal stress under different loading patterns are compared in Figure 7. The peak value of the maximal principal stress at the AC tooth was assumed to equate to the ultimate dentin strength and the average stress to the fatigue strength. When the top of a 45-degree cusp was loaded, the tensile limits of the dentin were exceeded for all the gold-alloy restored teeth. When the middle was loaded, the peak principal stresses were reduced by approximately 17% to 20%, and the average stresses were reduced by approximately 15% to 19%. The tensile limits were only reached for the FF tooth. When loading occurred on the bottom of a 45-degree cusp or the top of a 60-degree cusp, the peak stresses were reduced by approximately 29% to 34%, and the average stresses were reduced by approximately 31% to 33%. All test teeth had lower stress values than the AC tooth.

As for the glass-fiber restored teeth, the tensile limits of dentin were exceeded when the top of a 45-degree cusp was loaded. When the middle was loaded, the peak stress values were reduced by approximately 14% to 15%, and the average stress values declined approximately 15% to 25%. All test teeth induced lower stresses than the AC tooth, and the CF tooth exhibited the lowest stress among all 4 teeth. With loading on the bottom of a 45-degree cusp or the top of a 60-degree cusp, the peak and average values of the maximal principal stresses were reduced by approximately 38% to 43%.

The von Mises stress measured at the composite resin and glass-fiber post under different loading patterns are reported in Figure 8. Stresses introduced at the composite resin were reduced by approximately 12% with loading on the middle of a 45-degree cusp, and by 25 to 29% with loading on the bottom or when the cusp angle was 60 degrees. Stresses at the glass-fiber post with loading on the middle of a 45-degree cusp were approximately 10% lower than those exerted by loading at the top and were 23% lower when loading on the bottom or when the cusp angle was 60 degrees.

DISCUSSION

This study investigated the mechanical behavior of restored teeth with extensive coronal dentin loss and the influence of occlusal design on stress distribution. The mechanical characteristics of teeth with different ferrule configurations and post materials were examined. Simulations with gold-alloy posts found that stress concentration in the remaining dentin was higher in the tooth with a facial ferrule than in those with other ferrule configurations. The results of the current study, that the gold-alloy PF and CF teeth found the lowest stress when loaded on the top of a 45-degree cusp, are consistent with previous observations,[7,8] which may be



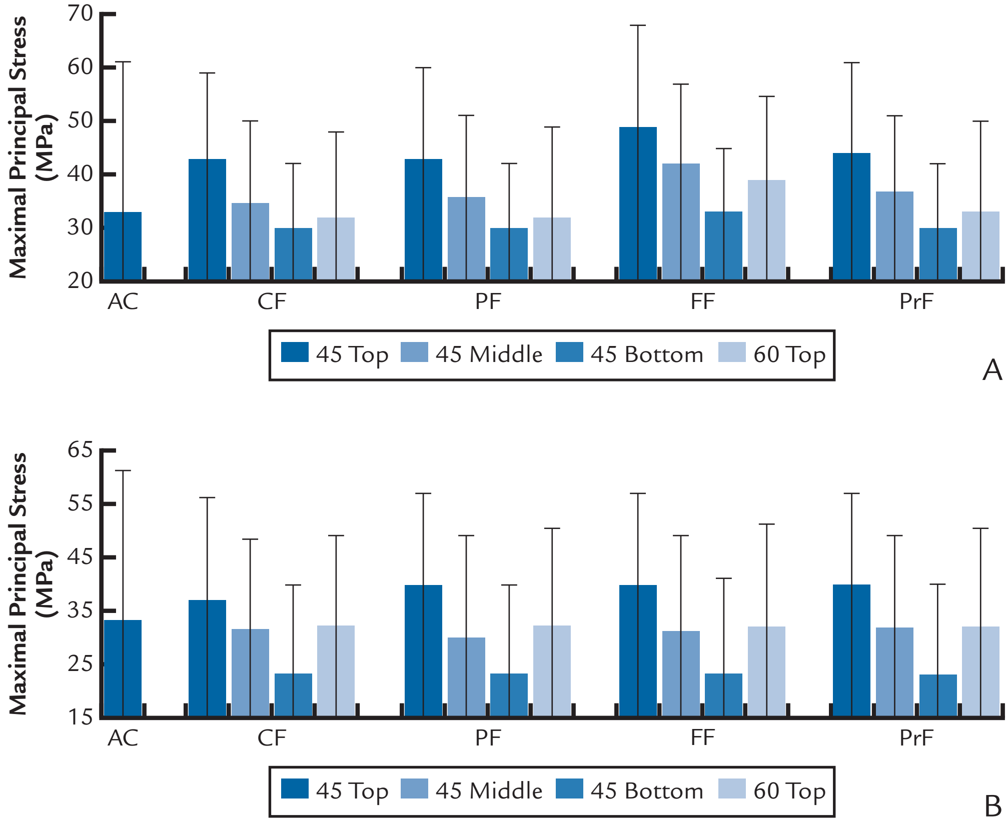
6 Maximal principal stress contours of palatal ferrule tooth under different loading procedures. A, Gold-alloy-post restored teeth. B, Glass-fiber-post restored teeth. 1. Load on top of 45-degree cusp; 2. Load on middle of 45-degree cusp; 3. Load on bottom of 45-degree cusp; 4. Load on top of 60-degree cusp.

related to the position of the coronal defect because the oblique forces on the maxillary premolars were applied on the palatal side and directed toward the buccal side.

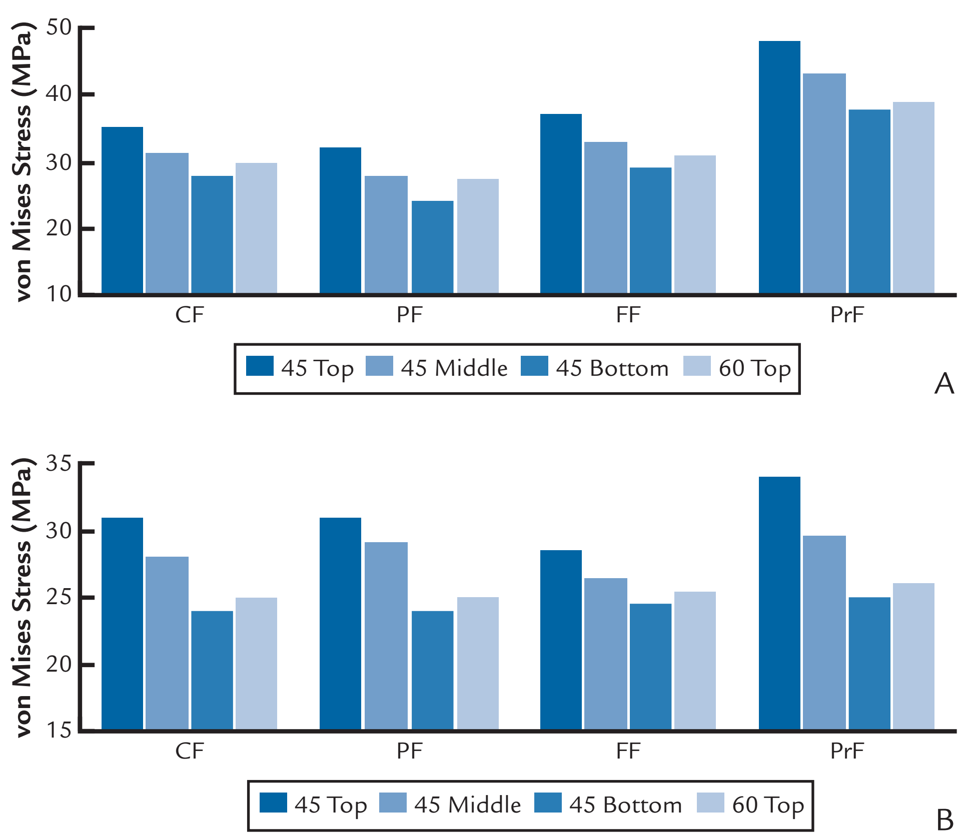
For teeth with glass-fiber posts, the principal stresses in the remaining dentin were more homogeneous. According to some studies, this may be due to the similar elastic moduli of the dentin and the glass-fiber post.[14] The influence of occlusal contact and cusp inclination also was analyzed, and the partial ferrule effect was taken into account. The maximal principal stress was gradually decreased as the loading position moved from the top to the bottom of the cusps and as the facial cusp inclination was reduced. When the loading force was applied to the middle and bottom of the facial cusp, the main oblique torque gradually reduced. The peak and average principal stresses for the AC cast, when loaded on the top, can be considered as “safe levels”; for gold-alloy casts, when loaded on the top of the cusps, high principal stresses at the root region were found to be risk indicators for root fracture. Loading at the middle of the cusps effectively reduced the peak and the average stresses to safe levels for the CF, PaF, and PrF casts but not for the FF cast.

When the glass-fiber post was used, the peak von Mises stress value on the composite resin core ranged from 32 to 48 MPa when loaded on the top of 45-degree cusps; based on previous studies, this indicates a cohesive failure risk.[15,16] When loaded on the middle of the cusps, all glass-fiber casts had less principal stress than the AC cast and less von Mises stress occurred in the glass-fiber post. In addition to the loading position, increasing the cusp angle also reduced the tensile stress. The lever arm of the oblique load was reduced when the facial cusp angle was 60 degrees, and there was a substantial decrease in tensile stress in the apical root region. In the simulations with gold-alloy posts, the root dentin found lower stress concentration compared with that of the AC tooth, regardless of the position of the partial ferrule.

To improve the mechanical stability and long-term success of post-and-core restorations, modifying the occlusal



7 Maximal principal stress (peak and average values) measured at dentin for different loading procedure. A, Gold-alloy-post restored teeth. B, Glass-fiber-post restored teeth.



8 Von Mises stress measured on composite resin and glass-fiber-post under different loading procedures. A, Peak stress measured on composite resin. B, Peak stress measured on glass-fiber-post.

design of maxillary premolars with large-scale tissue loss has many advantages, as found by this numerical simulation. First, for teeth with limited coronal dentin at the loading location, it was important to lower the oblique forces by reducing the lateral occlusal contact area and by preventing contact on the top of the facial cusp, thus protecting the remaining dentin from fracture. Second, when teeth have a coronal defect where the load is applied, for instance, the maxillary premolars with palatal dentin loss and no ferrule, the risk of restoration failure and root fracture should be considered. The overloading risk at the apex dentin cannot be improved unless the oblique load is only applied to the bottom of a high facial cusp or to a low cusp. Even though the tooth is restored with a glass-fiber post and a composite resin core, it is difficult to guarantee sufficient adhesive strength and the long-term stability of the restoration.

Two limitations of this study should be addressed in future work. First, the mechanical behavior of the periodontal ligament would be better described by an elastic anisotropic nonlinear discrete cast, according to the orientation and assignment of fibers.[17] Second, the perfect bonding interface disregards the different degree of bonding between the restoration material and the dentin. The cementation layer should be analyzed to establish the influence of this factor on stress distribution.

CONCLUSIONS

Maxillary premolar casts had different biomechanical characteristics for different ferrule configurations. When the tooth had only a facial ferrule left above the gingiva and was restored with a gold-alloy post, it exhibited the highest local stress on root dentin. These stress levels indicate a substantial risk of overloading in such situations. By loading on the middle or bottom of the facial cusp and by reducing facial cusp inclination, local stress concentration can be reduced.

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