Finite Element Analysis of Stress Distribution of 2 Different Tooth Preparation Designs in Porcelain-Fused-to-Metal Crowns

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Purpose: The aim of this clinical simulation study was to investigate the effect of anatomic and nonanatomic occlusal preparation design on stress distribution in different metal-ceramic crowns and tooth and bone. ***Materials and Methods:*** For the finite element analysis method, a 2-dimensional mathematical model of a mandibular second premolar tooth and its supporting tissues was used. The analysis was performed by using a structural analysis program. Four groups were designed: gold-palladium alloy/anatomic occlusal preparation (Au-Pd/A), Au-Pd alloy/nonanatomic (flat) occlusal preparation (Au-Pd/N), nickel-chromium alloy/anatomic occlusal preparation (Ni-Cr/A), and Ni-Cr alloy/nonanatomic occlusal preparation (Ni-Cr/N). A distributed type load of 400 N (total) was applied to the centric stop points on the tip of the buccal cusp and on the central developmental groove in centric occlusion to all types of restorations. ***Results:*** The results demonstrated that shear stresses in the dentin tissues and restorations in Au-Pd/A and Ni-Cr/A were similar. The shear stresses within the restorations in Au-Pd/N and Ni-Cr/N were similar. ***Conclusion:*** Anatomic occlusal preparation designs were advantageous in stress distribution in the dentin tissue. Nonanatomic occlusal preparation designs were found to be advantageous in the stress amount and distribution in the porcelain structure. Occlusal preparation designs and restorative materials showed no differences in stress distribution and amount in the pulp tissue and bone tissues. *Int J Prosthodont 2006;19:85–91.*

Careful attention to every detail of tooth preparation is imperative during the preparation of crowns. This ensures that subsequent techniques are readily and correctly accomplished.[1,2] A successful metal-ceramic crown preparation requires considerable tooth reduction wherever the metal substructure is to be veneered with dental porcelain; only with sufficient reduction can the darker color of the metal substructure be masked and the veneer duplicate the appearance of natural tooth. The porcelain veneer must have a certain minimum thickness for an esthetic result; thus, the metal-ceramic preparation is one of the least conservative of tooth structure.[1]

Metal-ceramic crowns are the most common type of crown used in the posterior region of the mouth.[3] Numerous claims have been made about the potential for improved coping and framework designs based on the higher elastic modulus of nickel-chromium and cobalt-chromium alloys.[4–6] The metal-ceramic crown is stronger than the porcelain jacket crown and has a generally superior marginal fit.[1]

Few studies have investigated stress distribution on the tooth and supporting tissues using different tooth preparation procedures and restorative materials. The aim of the present study was to examine and compare

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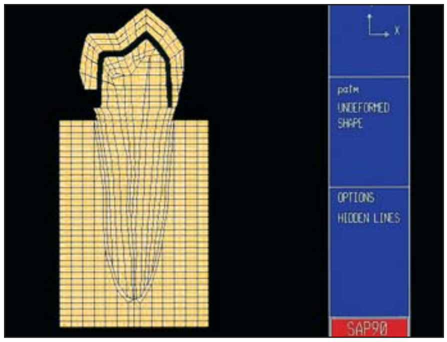

Fig 1 Finite element model of anatomic occlusal preparation design.

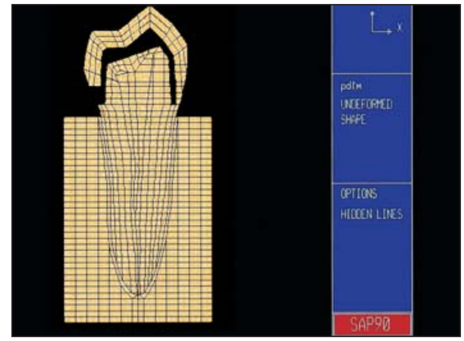

Fig 2 Finite element model of nonanatomic occlusal preparation design.

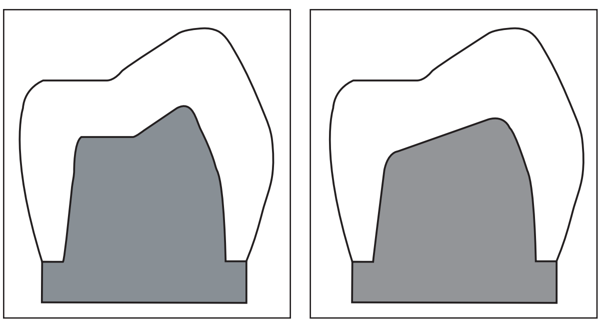

Fig 3 Schematic drawing of preparations. *(Left)* Anatomic occlusal preparation design. *(Right)* Nonanatomic occlusal preparation design.

the effect of 2 different tooth preparation designs on the stress distribution in 2 different metal-ceramic crowns, tooth and bone tissue using finite element analysis (FEA) to simulate clinical loading conditions.

Materials and Methods

In this study, the FEA method was used with a structural analysis program (SAP90; Computers and Structures). For the FEA, a 2-dimensional mathematical model was generated of the central buccolingual section of a mandibular second premolar tooth.

The geometry of the tooth model has been described by Wheeler.[7] The X and Y coordinates for each mathematical model were determined. The analysis was performed on an IBM-compatible personal computer (Pentium IV processor, 512 MB RAM, 70 GB hard disk) running the SAP90 program. The outputs were transferred to SAPLOT program (Computers and Structures) to display the resulting stress values.

Occlusal reduction was prepared according to the anatomic forms of the cusps in the anatomic occlusal preparation design (Fig 1). Occlusal reduction was then prepared as a flat reduction regardless of the anatomic forms of the cusps in the nonanatomic occlusal preparation design (Fig 2). A schematic drawing of differences between the 2 occlusal preparation designs is shown in Fig 3. A nickel-chromium alloy (Ni-Cr, Remanium CS, Dentaurum) and a gold-palladium alloy (Au-Pd, J. F. Jelenko) were selected for the metal-ceramic crowns. A metal thickness of 0.5 mm and porcelain thickness (feldspathic porcelain, Klema) of 1.5 mm were used for each group. A 1-mm shoulder finish line and 6-degree total occlusal convergence were designed for all groups. Each mathematical model consisted of 885 elements with 931 nodes. Four groups were designed:

1. Au-Pd/A: The metal-ceramic crown with a Au-Pd alloy coping and anatomic occlusal preparation design
2. Au-Pd/N: The metal-ceramic crown with a Au-Pd alloy coping and nonanatomic occlusal preparation design
3. Ni-Cr/A: The metal-ceramic crown with a Ni-Cr alloy coping and anatomic occlusal preparation design
4. Ni-Cr/N: The metal-ceramic crown with a Ni-Cr alloy coping and nonanatomic occlusal preparation design

A distributed type load of 400 N (total load) was applied to the centric stop points on the tip of the buccal cusp (node 914, 200 N) and on the central developmental groove (node 881, 200 N) in centric occlusion to all 4 models (Fig 4). The final element on the x-axis for each group was assumed to be fixed, which defined boundary conditions. The metal-ceramic bond was assumed to be ideal. Residual stresses resulting from thermal contraction differentials between metal and porcelain were assumed to be negligible. The cement thickness layer was ignored. It was assumed that enamel tissue was completely removed during tooth preparation. The structures in the mathematical model were assumed to be linearly elastic, homogeneous, and isotropic. Poisson's ratio (ν) and the modulus of elasticity (ϵ) of oral tissue and crown materials were determined from the literature[8–15] and are presented in Table 1.

Table 1 Mechanical Properties of Oral Tissues and Prosthetic Materials in FEA Evaluations

Materials and oral tissues	Modulus of elasticity (ϵ) (MPa)	Poisson's ratio (ν)	Reference
Bone	13,700	0.30	8–12
Periodontal ligament	69	0.45	13
Dentin	18	0.33	14
Ni-Cr	206	0.33	15
A-Pd	89,500	0.33	4
Pulp	2	0.45	13
Feldspathic porcelain	82,800	0.33	10

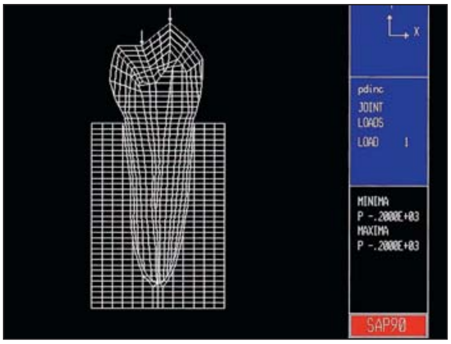

Fig 4 Localizations of load applied to finite element model (node 914, tip of the buccal cusp; node 881, central developmental groove).

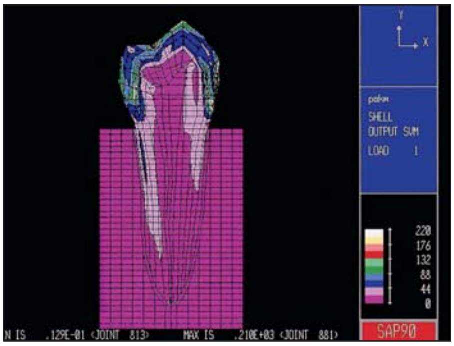

Fig 5 Distribution of shear stress within the restoration in Au-Pd alloy/anatomic occlusal preparation.

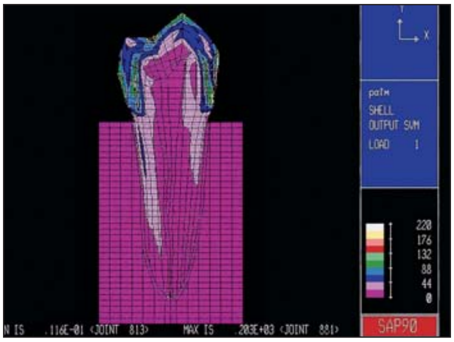

Fig 6 Distribution of shear stress within the restoration in Ni-Cr alloy/anatomic occlusal preparation.

Results

In this study, shear stresses in the restoration, dentin, pulp, and bone tissues were evaluated.

Restorations

Stress distribution and localization within the restorations in Au-Pd/A and Ni-Cr/A were observed to be similar (Figs 5 and 6). The highest stress values occurred on the tip of the buccal cusp and on the central developmental groove. Shear stress was concentrated in the metal coping and on the buccal margin of the porcelain structure. A maximum shear stress of 210 MPa existed on the central developmental groove (node 881) in Au-Pd/A. A maximum shear stress of 203 MPa existed on the central developmental groove (node 881) in Ni-Cr/A.

The stress distribution that developed within the restorations Au-Pd/N and Ni-Cr/N were similar (Figs 7 and 8). Maximum shear stresses occurred on the central developmental groove in Au-Pd/N and Ni-Cr/N. While a maximum shear stress of 188 MPa (node 881 central developmental groove) occurred in Au-Pd/N and an intensive stress area formed in the coping material, a maximum shear stress of 193 MPa (node 881) occurred in Ni-Cr/N, which was less than that of Au-Pd/N. Low stress values existed in the porcelain structure in both groups and high stress values existed in the metal alloy, especially at the lingual surface of the metal coping.

The values of shear stress within the restorations are shown in Table 2 and in Fig 9.

Dentin Tissue

When the stress distribution that developed in the dentin tissue was examined, Au-Pd/A and Ni-Cr/A were found to be similar. Very low stress values oc-

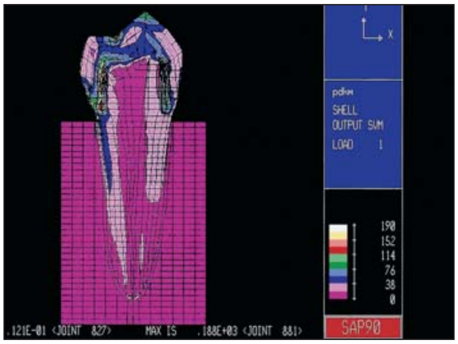

Fig 7 Distribution of shear stress within the restoration in Au-Pd alloy/nonanatomic occlusal preparation.

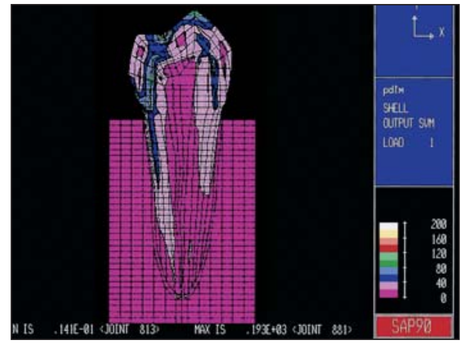

Fig 8 Distribution of shear stress within the restoration in Ni-Cr alloy/nonanatomic occlusal preparation.

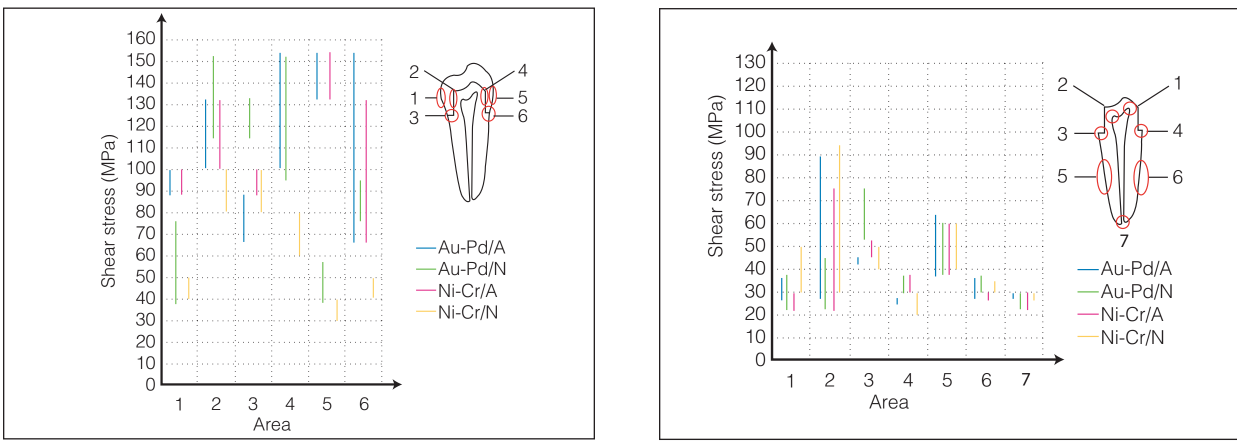

Fig 9 The values of shear stress *(left)* within the restorations and *(right)* within the dentin.

Table 2 Values for Shear Stress Within the Restorations (MPa)

Area	Au-Pd/A	Au-Pd/N	Ni-Cr/A	Ni-Cr/N
1	88–100	38–76	88–100	40–50
2	100–132	114–152	100–132	80–100
3	66–88	114–133	88–100	80–100
4	100–154	95–152	88–100	60–80
5	132–154	38–57	132–154	30–40
6	66–154	76–95	66–132	40–50

curred on the occlusal surface of the tooth. Highest stress values existed in the dentin tissue on the lingual pulp horn in Au-Pd/A and Ni-Cr/A (Figs 10 and 11). A maximum shear stress of 89.6 MPa occurred in the dentin tissue on the lingual pulp horn in Au-Pd/A. It was observed that a shear stress of 27 MPa occurred at the buccal margin and a shear stress of 45 MPa occurred at the lingual margin in Au-Pd/A. This stress was transmitted from the margins to the root of the tooth (Fig 10). A maximum shear stress of 74.9 MPa existed in the dentin tissue on the lingual pulp horn in Ni-Cr/A. Stress was transmitted from the preparation surface to the cervical area and the pulp tissue in Ni-Cr/A. It was found that a shear stress of 37.5 MPa existed at the buccal margin and a shear stress of 52.5 MPa existed at the lingual margin in Ni-Cr/A (Fig 11). At the root of the tooth, shear stress was transmitted to the periodontal ligament in Au-Pd/A and Ni-Cr/A with regular increase. This stress was concentrated on the lingual surface of the root (Figs 10 and 11).

In the dentin tissue in Au-Pd/N, development of a maximum shear stress of 71 MPa at the lingual margin was observed (node 767). The stress was transmitted from the preparation surface to the cervical area and the

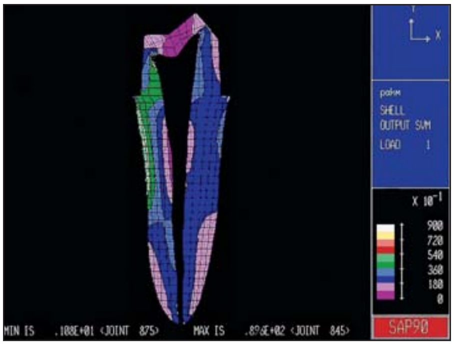

Fig 10 Distribution of shear stress within the dentin tissue in Au-Pd alloy/anatomic occlusal preparation.

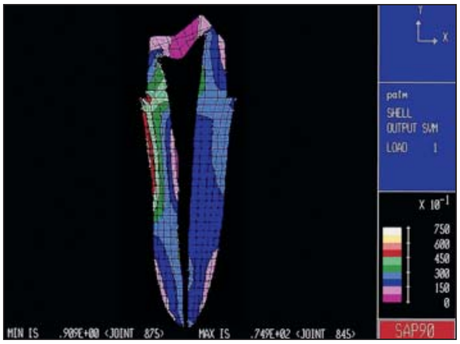

Fig 11 Distribution of shear stress within the dentin tissue in Ni-Cr alloy/anatomic occlusal preparation.

Table 3 The Values for Shear Stress Within the Dentin Tissues (MPa)

Area	Au-Pd/A	Au-Pd/N	Ni-Cr/A	Ni-Cr/N
1	27–36	22–37	22–30	30–50
2	27–89	22–45	22–75	30–94
3	42–45	52–71	45–52	40–50
4	25–27	30–37	30–37	20–30
5	36–63	37–60	37–60	40–60
6	27–36	30–37	27–30	30–35
7	27–30	22–30	22–30	27–30

pulp tissue. A stress of 37.5 MPa occurred at the buccal margin. In the root, stress was increasingly transmitted from the pulp tissue to the periodontal ligament and was located on the lingual surface of the root (Fig 12).

Upon examination of the stress distribution in the dentin tissue in Ni-Cr/N, it was observed that the lowest stress value existed on the occlusal surface. The highest stress value of 94.2 MPa existed in the dentin tissue on the lingual pulp horn. In the crown, stress was transmitted from the preparation surface to the pulp tissue and cervical area. In the root, the stress was increasingly transmitted from the pulp tissue to the periodontal ligament and was located on the lingual surface of the root (Fig 13).

The values of shear stress within the dentin tissues are shown in Table 3 and in Fig 9.

Pulp Tissue

Shear stresses in the pulp tissues were similar in all groups and were located in the apex of the pulp tissue.

Bone Tissue

Shear stresses in the bone tissues were similar in all groups and were located in the bone tissue around the apex of the root.

Discussion

Tooth preparation design is very important in the success of fixed partial dentures. There are few studies in the literature about the effect of stress distribution when different prosthetic restorations are applied to different tooth preparation designs. Anatomic occlusal preparation is sometimes neglected and teeth are prepared with a flat occlusal reduction, regardless of the anatomic forms of the cusps. Therefore, the present study aimed to examine the effect of occlusal preparation design on the stress distribution in the metal-ceramic crown, the tooth, and the supporting tissues.

All materials were presumed to be linearly elastic, homogeneous, and isotropic in the present study. However, living tissue and materials in nature are not homogeneous.[16–18] According to Rosenstiel et al[1] and Shillingburg et al,[6] in the typical metal-ceramic crown, metal thickness is 0.3 to 0.5 mm and porcelain thickness is 0.7 to 1.2 mm. The metal and porcelain thicknesses used in the present study were 0.5 to 1.5 mm. Loads between 424 and 583 N were applied on the mandibular premolar teeth in previous studies.[19–21] A total load of 400 N was applied to all groups in the present study.

In this study, it was observed that stress increased by approximately 4 times in the porcelain structure

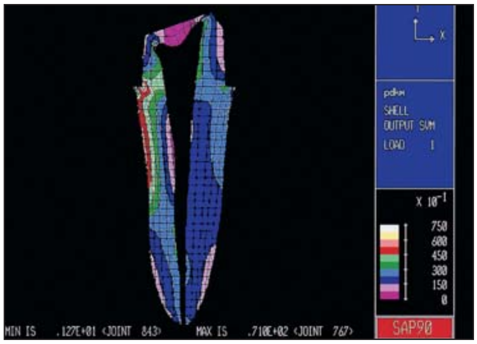

Fig 12 Distribution of shear stress within the dentin tissue in Au-Pd alloy/nonanatomic occlusal preparation.

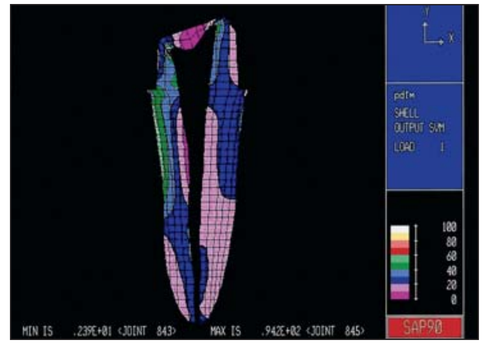

Fig 13 Distribution of shear stress within the dentin tissue in Ni-Cr alloy/nonanatomic occlusal preparation.

when the nonanatomic occlusal preparation design was used, compared to the anatomic occlusal preparation design. In flattened occlusal preparation designs, the flexibility of the metal structure decreased as a result of the increase in the thickness of the coping material. So, it is concluded that less shear stress developed in the porcelain structure. Therefore, one may except that a restoration with nonanatomic occlusal preparation will be structurally strong. El-Ebrashi et al[22] concluded that partial dentures with a chamfer margin and flat occlusal preparation were structurally stronger than those with knife-edge proximal margins and anatomic occlusal protection. El-Ebrashi et al[23] used photoelastic stress analysis methods in their study. They examined the stress distribution that developed on the gold inlays and onlays on the mandibular second molar tooth with different patterns of occlusal reduction. They reported that the stress concentration factor computed for a flat reduction of cusp was 40% less than that for anatomic reduction of the cusp because of the increase in the thickness of the restoration. The results of the present study were similar to the findings of El-Ebrashi et al.[22,23]

When the anatomic occlusal preparation designs were compared, it was observed that the increase in the modulus of elasticity of the coping material resulted in the decrease in the stress values in the restoration. On the other hand, it increased the stress in the dentin tissue, especially at the margins.

In the comparison of the nonanatomic occlusal preparation designs, it was observed that the increase in the modulus of elasticity of the coping material reduced stress in the restoration. However, it decreased the stress at the lingual margins, and no significant difference was observed in the stress distribution in the dentin tissue. When the modulus of elasticity of the coping material increased, the stress in the coping material decreased, regardless of the type of occlusal preparation used.

Upon examination of shear stresses within the dentin tissues, it was observed that the anatomic occlusal preparation design was advantageous in distributing stress in the metal-ceramic crown with a Ni-Cr alloy coping. The anatomic occlusal preparation design had more homogenous stress distribution than the nonanatomic occlusal preparation design in the metal-ceramic crown with a Au-Pd alloy coping. Therefore, occlusal preparation design must be anatomic.

In all groups except for Au-Pd/N, maximum shear stress was located in the dentin tissues on the lingual pulp horns and concentrated at the lingual half of the tooth in the crown because of the anatomy of the pulp. Likewise, it was considered that the stresses were concentrated at the lingual surface of the roots and the lingual margins because the lingual pulp horn inclined to the cervical direction rather than the buccal pulp horn.

Previous finite element and strain-gauge studies have found that stresses concentrate in the thin cervical enamel area, and the magnitude of these stresses exceeds the known failure stresses for enamel.[24,25] The tensile and shear stresses generated in the cervical region cause breakdown of the bonds between the hydroxyapatite crystals, leading to crack initiation in the enamel and an eventual loss of enamel and the underlying dentin.[26–29]

In this study, it was observed that repeated high stress at restorations with a low modulus of elasticity could cause abfraction lesions at the crown margins of the dentin tissue in the nonanatomic occlusal preparation design. However, this probability was very low in the anatomic occlusal preparation design.

It was also shown that the occlusal preparation design and different restorative materials showed no differences on the stress in the pulp and the bone tissue.

Stress distribution and load transmission in restorations were affected by the design of the prosthetic structure, loads, tooth preparation, cementation, and properties of the prosthetic materials used.[30,31]

Conclusion

It appears that different tooth preparation designs may influence stress distribution in both dentin and porcelain structure but not in pulp and bone tissues. It is conceded that the relevance of this type of research design cannot be extrapolated to clinical situations. The simulation of time-dependent clinical occlusal loading in the context of a biologic system's adaptive capacity can be modeled only partially in a laboratory. Therefore this study's results must be interpreted with caution. From the results of this study, the following conclusions were drawn:

1. Anatomic occlusal preparation designs were advantageous for stress distribution in the dentin.
2. Nonanatomic occlusal preparation designs were advantageous from the point of view of stress distribution and amount of stress in the porcelain structure.
3. Occlusal preparation designs and restorative materials showed no differences in distribution and amount of stress in the pulp tissues and bone tissues.

Acknowledgment

The authors would like to thank Serhat Osman Oktay for his help in the preparation of the manuscript and figures.

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