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COMPARISON OF THERMAL STRESS ON VARIOUS RESTORATIVE POST AND CORE MATERIALS GENERATED BY ORAL TEMPERATURE CHANGES USING THREE DIMENSIONAL FINITE ELEMENT ANALYSIS

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ABSTRACT

Background and Aim: The purpose of this study was to compare thermal stress on various restorative post and core materials generated by oral temperature changes using three dimensional finite element analysis.

Materials and Methods: Three dimensional model of a mandibular right first premolar restored with a metal-ceramic crown and a dowel – core system was constructed. The thermal load applied to the three dimensional tooth model simulated the draught of hot (60°C) and cold (15°C) food or beverages for 5 seconds. Temperature distribution and thermal stress was calculated at 8 points in von Mises value of MPa, determined on the buccolingual plane using thermal loading function of finite element analysis programme.

Results: The temperature gradient of the metal post and cores was smaller than that of the resin cores because of the high thermal conductivity of the former materials. Thermal changes and post-core materials have a significant effect on the thermal stress concentrations particularly located in the restorations. The gold post and core system showed the smallest thermal stress. The combination of prefabricated stainless steel post and amalgam core generated the highest thermal stress in the restoration and dentin. Cast post-core systems generated lower thermal stress when compared to prefabricated dowel and core materials.

Conclusions: Cast gold post-core or non-metallic prefabricated posts-composite core materials generated better thermal stress distribution and their use in clinical practice could be recommended.

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Orjinal Araştırma

ORAL SICAKLIK DEĞİŞİKLİKLERİNİN FARKLI YAPIDAKI RESTORATİF POST VE KOR MATERYALLER ÜZERİNDEKİ TERMAL STRES ETKİSİNİN ÜÇ BOYUTLU SONLU ELEMANLAR ANALİZİ İLE KARŞILAŞTIRILMASI

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ÖZ

Amaç: Bu çalışmanın amacı, oral sıcaklık değişikliklerinin farklı yapıdaki restoratif post ve kor materyaller üzerinde meydana getirdiği termal stresleri üç boyutlu sonlu elemanlar analizi ile karşılaştırmaktır.

Gereç ve Yöntem: Termal stres analizi için, içinde post ve kor bulunan alt sağ 1. premolar dişe ait anatomik ve protetik yapılar ile birlikte, dişi çevreleyen sert ve yumuşak dokuların üç boyutlu sonlu elemanlar modeli oluşturulmuştur. Modele 5 saniye süreyle soğuk (15°C) ve sıcak (60°C) olmak üzere iki farklı sıcaklık koşulu uygulanmış ve sıcaklık dağılım ve termal stres analizi gerçekleştirilmiştir. Sıcaklık dağılım ve termal stres ölçümleri von Mises MPa değeri ile bukko-lingual model kesiti üzerinde belirlenen 8 noktada sonlu eleman analizi metodunun termal yükleme fonksiyonu kullanılarak yapılmıştır.

Bulgular: Tek parça döküm post-kor ve prefabrik metal post-amalgam kor sistemleri, yüksek termal iletkenlik katsayıları sebebiyle, metal post-kompozit kor ve metal olmayan post-kompozit kor sistemlerine göre, incelenen model katmanları arasında daha düşük sıcaklık farklılıklarının oluşmasına yol açmışlardır. En düşük termal stres oluşumu, döküm altın post ve altın kor sisteminde, en yüksek termal stres oluşumu, prefabrik paslanmaz çelik post ve amalgam kor sisteminde meydana gelmiştir. Tek parça döküm post-kor sistemleri, iki parça prefabrik post–kor sistemlerine kıyasla, daha avantajlı termal stres sonuçları vermektedir.

Sonuçlar: Döküm altın post-kor ve metal olmayan post-kompozit kor kombinasyonu daha olumlu termal stres dağılımı göstermişlerdir. Bu sebeple klinikte kullanımları tavsiye edilebilir.

Anahtar Kelimeler: Sonlu Eleman Analizi, Post, Sıcaklık dağılımı, Termal stres,

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INTRODUCTION

Post-core restorations are widely used for building up endodontically treated teeth with extensive loss of hard tissue in order to enhance the longevity of teeth and to provide retention for a fixed restoration. It has been reported that a vast number of restored endodontically treated teeth clinically function with the use of intraradicular devices.[1] These devices vary from a conventional custom cast post and core to commercially available prefabricated post systems incorporated with core materials.[2] Traditionally, cast post and cores were often considered as an accurate solution as they are fabricated on a model obtained from the root cavity. However, the high stiffness of metallic alloys may cause root fractures.[3] In the last few decades, prefabricated metal and non-metal posts combined with resin or amalgam cores are considered viable treatment alternatives. Because of their high strength, metallic materials such as gold alloy, stainless steel and titanium are widely used as conventional post materials.[4] In the last decade, non metallic posts such as composite, carbon fiber or glass fiber posts gained popularity as theoretically acceptable alternative materials. These materials can reproduce the natural load transmission mechanisms well, because their stiffness is very close to dentin.[4,5] However, their utilization may require special care when the restoration of a wide-flared root cavity is entailed, as the larger quantity of cement used for filling gaps between the post and root cavity walls causes inhomogeneity in the mechanical behaviour of the restored tooth structure.[4-6]

A number of comprehensive reviews on biomechanical aspects and different failure mechanisms involved in post-endodontic restorations have been published previously.[6-8]

Another important aspect that must be considered is that oral cavity may undergo rapid thermal changes due to heat flow during consumption of hot and cold foods. Palmer et al. reported that temperature extremes could be reached at the natural tooth surface on 13 human subjects ranged from 0 °C to 67 °C.[9]

It can be assumed that there may be a considerable gradient of temperature when teeth at constant body temperature come into contact with hot or cold stimulants. Consequently, because of mismatches in thermophysical properties of a tooth and restorative materials, thermal stresses may develop at interfaces.[10,11] An endodontically treated tooth with post-core restoration comprises of several restorative materials (post, cement, core, crown, etc.) and is certainly susceptible to thermal stresses because of their high degree of inhomogeneity. Therefore thermally induced stresses may further lead to fracture of the dental structure, leakage or failure of post-core restoration.[11]

Even though internal stress caused by thermal expansions and contractions is clinically important, there is limited thermal analysis data in literature about post and core restorations. The examination of thermal changes at the interfaces between different restorative materials presents experimental difficulties. In this aspect, finite element analysis (FEA), enables calculation of temperature, stress, strain, and deformation at interfaces of discretionally shaped 3D finite element model representing a structure under static loading on tooth-restoration complex.[12,13]

Several researchers have studied the mechanical properties of endodontically treated teeth by finite element method in elastic analyses; however, limited number of investigators evaluated thermal stress.[10,14,15] Thus, it may be valuable to compare the temperature distribution characteristics of different restorative materials which may affect the thermal stress distribution. The purpose of this study was to investigate the temperature and thermal stress distribution in a model of endodontically treated tooth restored with various post and core materials using the FEA method.

MATERIALS AND METHODS

A 3-dimensional finite element model of mandibular first premolar with its supporting structures was constructed according to Wheeler's atlas of tooth form using computational software (3D-Doctor, Able Software, U.S.A.). The standard model included a metal ceramic crown and a parallel post, 13 mm in length and 1,5 mm in diameter. The average thickness of the zinc phosphate cement layer and resin cement were 0.4 mm and 0.1 mm respectively.

The model used in this study was 12 mm in width, 15 mm in length and 16 mm in height. It was consisted of 70332 elements and 13215 nodes (Figure 1). In modelling the cement layer, the interface between the cement layer and the other structures had no gap or slip. The model was constrained at the bottom boundaries. The investigated eight material combinations of the post and cores are listed in Table 1. All materials and vital tissues were presumed elastic, homogeneous, linear and isotropic which included continual interfaces between materials. The mechanical and thermal properties of each material and tooth were obtained from the literature survey and they are presented in Table 2.

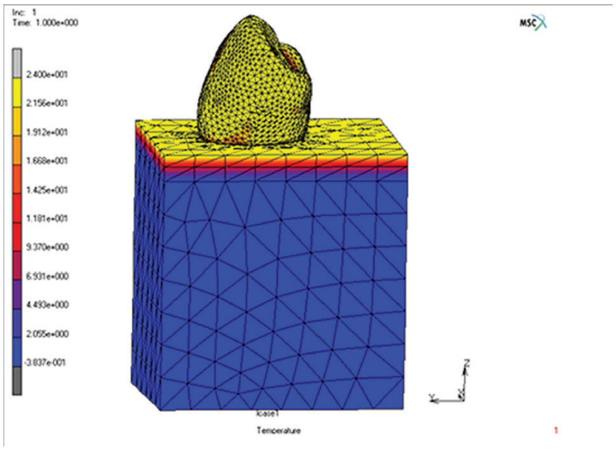


Figure 1. Three dimensional finite element model of mandibular first premolar.

Finite element analysis included two sequential stages. First, an initial transient thermal analysis was performed using computational software (Marc/Mentat, MSC Software, USA) to calculate the temperature distributions at determined points with time. The initial temperature of the entire model was set to 36°C and thermal loads resulting from bulk temperatures of 15°C (cold stimulus) and 60°C (hot stimulus) were applied for 5 seconds. Afterwards the model's temperature was left to turn to 36°C for 10 seconds. These temperature ranges were selected with reference to previous studies describing the temperature extremes measured in the oral environment.[9,15] The heat transfer coefficient was determined as 4.10×10^{-4}(cal/mms°C).[14] The arithmetical mean of temperature flow was calculated at axially located 5 points (A, D, E, G, H) that were determined on the buccolingual cross-section of the 3D model (Figure 2).[9,11,14] More apically located points were omitted because minimal temperature changes were anticipated in the apical third of root.

In the second stage, in order to evaluate thermal stresses, structural analysis was carried out after completing thermal analysis. The temperature was assumed to follow a linear function in time within each element. Thermal stress distribution was calculated in von Mises equivalent stress values. The von Mises stress σ_{eqv} is defined as

$$\sigma_v = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}}$$

where σ_1, σ_2, and σ_3 are the principal stress components.[16] In this study, σ_{eqv} has been considered as an indicator of the average stress level, where the higher the value, the higher the probability of failure initiation. Stress distribution with time was calculated and plotted at 8 critical points (A,B,C,D,E,F,G and H) located on the post-core and interfaces (Figure 2). The calculated numerical data were then transformed into color graphics to better visualize stress distribution. All stress values were indicated in megapascals (MPa). Descriptive statistics were used while evaluating data, using the median, minimum and maximum temperature values.

RESULTS

Temperature distribution for transient thermal analysis

Results from the transient thermal analysis are presented in Table 3. Type II gold distributed the temperature changes to

Table 1. The post and core materials used in this study.

Model acronym	Post material	Core material
GG	Type II Gold	Type II Gold
NN	Nickel-chromium	Nickel-chromium
AT	Titanium	Amalgam
RT	Titanium	Composite resin
AS	Stainless steel	Amalgam
RS	Stainless steel	Composite resin
RC	Carbon fiber	Composite resin
RG	Glass fiber	Composite resin

Table 2. The mechanical and thermal properties of materials and tissues.

Material	Density (10^{-6}kg/ mm^{3})	Modulus of elasticity (GPa)	Poisson's ratio	Thermal expansion coefficient (10^{-6}/C°)	Specific heat (10^{3} J/kg)	Thermal conductivity coefficient (J/mms C°)
Cortical bone [10, 22]	1.3	14.7	0.3	10	0.44	0.5868
Cancellous bone [10,22]	1.3	0.49	0.3	10	0.44	0.5868
Periodontal ligament [25]	1.04	0.00118	0.45	4.1	0.36	0.5
Gingiva [25]	1.04	0.00118	0.45	4.1	0.36	0.5
Dentin [10,25]	2.1	14.7	0.31	8.3	0.28	0.6276
Gutta percha [25]	0.9	0.186	0.45	54.9	0.22	0.48
Composite [10]	2.1	12	0.24	39.4	0.2	1.0878
Amalgam [10]	11.6	52.4	0.35	25	0.06	22.5936
Porcelain [10, 13, 22]	2.4	70	0.19	7.1	0.21	1.0042
Carbon fiber [10]	1.5	118	0.28	2.2	0.3	6.276
Titanium [10, 19]	4.51	112	0.33	11.9	0.54	21.9
Type II gold [10]	15	77.2	0.33	14.1	0.3	125.52
Glass fiber [15]	2.5	40	0.27	8.5	0.26	1.3
Stainless steel [10]	7.9	210	0.28	14.3	0.11	66.944
Nickel-chromium [10]	8.4	203	0.33	14.3	0.11	66.944
Resin cement [26]	2.24	18.6	0.28	30	0.197	0.976
Zinc phosphate cem. [10, 25]	2.6	22.4	0.35	35	0.12	1.294

Table 3. The minimum and maximum temperature values (C°) calculated at A,D,E,G and H points 5 seconds after introduction of cold and hot stimulants. Note that GG presented lowest and RG presented highest temperature change.

		Cold stimulus			Hot stimulus	
Model acronym	Min.	Median	Max.	Min.	Median	Max.
GG	15	15	22.18	57.95	57.95	49.74
NN	15	15	23.95	57.95	57.95	47.7
AS	15	15	23.96	57.95	57.95	47.69
AT	15	15	27.806	57.91	57.91	46.06
RS	15	15	31.911	57.94	53.8	45.537
RT	15	18.61	25.85	57.91	55.81	43.222
RC	15	16.83	27.845	57.86	57.86	38.55
RG	15	15	31.888	57.86	57.86	38.525

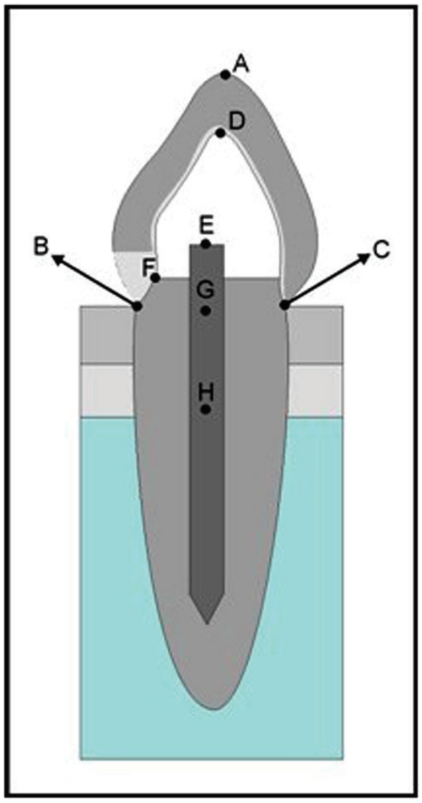
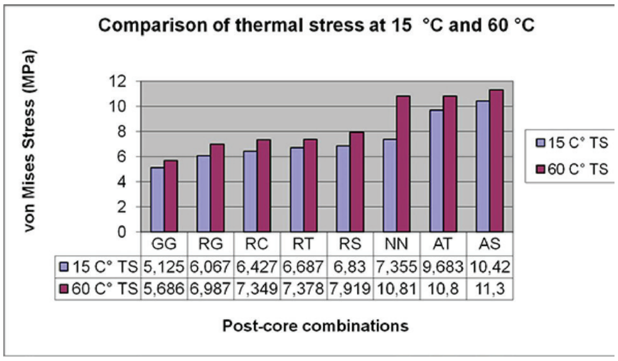


Figure 2. Eight points (A, B, C, D, E, F, G and H) determined on post, core and interfaces for calculation of temperature and thermal stress distribution.



	GG	RG	RC	RT	RS	NN	AT	AS
15 C° TS	5,125	6,067	6,427	6,687	6,83	7,355	9,683	10,42
60 C° TS	5,686	6,987	7,349	7,378	7,919	10,81	10,8	11,3

Figure 3. Mean thermal stress values calculated at determined points for post-core combinations, 5 seconds after introduction of cold and hot stimulus.

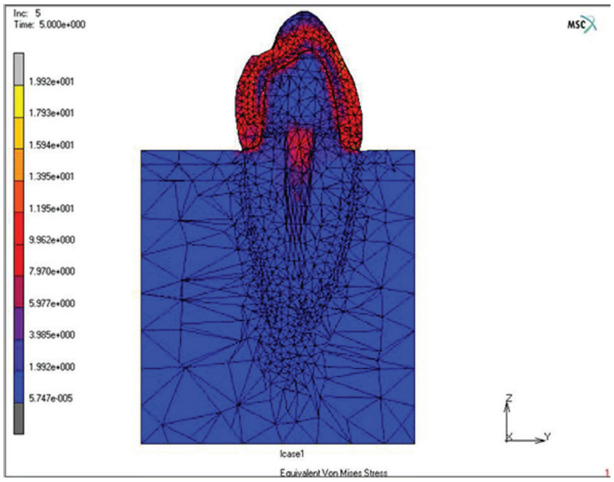


Figure 4. Thermal stress distribution in cast gold post-core, 5 seconds after introduction of 15 °C stimulus. Magnitudes of Von Mises stress are indicated with color code (MPa). Note, uniform stress distribution in core and servical third of root indicated with blue (yellow color indicates highest values of von Mises stress).

produce the smallest temperature differences in the range of 17.1 °C and 55.4 °C whereas the glass fiber dowel and resin core produced the highest temperature differences in the range of 19.5 °C and 53.1 °C respectively for cold and hot stimulants within the structures (Table 3). The temperature difference between the outer surface and inner structures was greater in the resin-core models RG, RC, RT and RS than in the metal-core models AT, AS, NN and GG, 5 seconds after the introduction of both cold and hot stimulants.

Thermal stress distribution

Maximum stress values obtained for cold and hot stimulus are presented in Figure 3. The cast gold post-core presented the lowest von Mises stress value of 5.125 MPa for cold stimulus (Figure 4). The combination of an amalgam core with stainless steel post generated the highest thermal stress value of 11.295 MPa for hot stimulus which was almost twice the value of gold post and core (Figure 5). For this combination, the highest thermal stress value was calculated at G point, the coronal one-third of the stainless steel post located in the amalgam core. At D, B and C points, higher thermal stress values were calculated where amalgam core interfaces with the metal substructure of the crown. The cold stimulus generated lower thermal stress values on 3D model when compared to hot stimulus. The magnitude of thermal stress was greater in the amalgam and cast metal core groups than in the resin core groups. No stress changes were evident in the root dentin, supporting bones, gingiva and periodontium.

DISCUSSION

In this study, the distribution of thermal stresses in a post-core restored tooth resulting from temperature

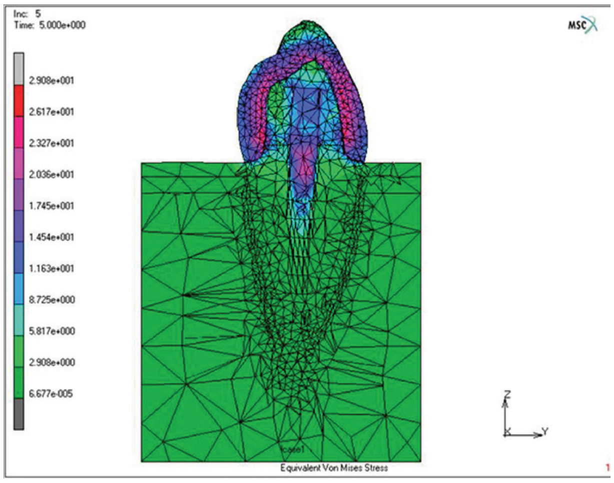


Figure 5. Thermal stress distribution in prefabricated stainless steel post-composite core, 5 seconds after introduction of 60 °C stimulus. Note, stress distribution concentrated in composite core and cervical third of stainless steel post indicated with purple color.

changes in oral cavity was investigated. The results of the present study led us to reject the null hypothesis that the temperature gradient and thermal stress distribution generated by cold and hot stimulants would not be affected by different post and core materials. Different restorative materials exhibited different stress distribution patterns for all post-core combinations.

Evolution of temperature distribution in the post-core restored tooth depends on the level of heterogeneity and specific combination of restorative materials included in the tooth structure. These two factors define the overall thermal properties of the restored tooth that finally drive temperature change rates as the tooth is exposed to thermal irritants.[17]

For cast post-cores and prefabricated posts and amalgam cores, the difference between temperatures calculated at the outmost point A and innermost point H was lower with respect to metal and non metal prefabricated posts combined with composite cores. Metals tend to be better heat conductors than non-metals. This may be attributed to the higher termal conductivity coefficient of metals (Type II Gold, 125.52; Stainless steel, 66.944; Amalgam, 22.59 J/mms C°)) than composite (1.0878 J/mms C°) and thus rapid diffusion of the oral cavity temperature to the inner structures of the restoration (Table 2). Thermal diffusivity of a material controls the time and rate of the temperature change as heat passes through a material. It measures the rate at which an object with non-uniform temperature reaches a state of thermal equlibrium.[18] Our results are in accordance with the results of a previous study, in that cast gold post-core and prefabricated metal posts combined with amalgam cores generated rapid thermal diffusion.[10]

For both cold and hot stimulus, the peripherical points A and D on crown presented a rapid temperature change, however inner points E, G and H presented different diffusion behaviours according to different restorative materials. Zinc phosphate or resin cement got adapted to the surrounding restorative layers and presented similar thermal behaviours which may be due to relatively low thickness of cement layers.[19] Minimal temperature changes were detected in root dentin and cortical bone. This may be attributed to the distance between thermal stimulant and those tissues or blood circulation which might have kept the tissues at body temperature during cold or hot stimulant application.[10,14]

Thermal conductivity, thermal diffusivity and linear coefficient of thermal expansion are important parameters in predicting the transfer of thermal energy through restorations since an unsteady state of heat transfer exists during ingestion of hot and cold food and beverages.[16,20] When dental structures are replaced with restorative materials, the thermal diffusivity of the tooth changes. The reaction of metallic, nonmetallic restorative materials and dentin to temperature changes may present variations because of different thermal conductivity and thermal expansion coefficients. These changes may create thermal stress on the restored tooth.[10,17]

The points B and C determined on the cervical third of the crown presented different thermal stress patterns. Nickel-chromium substructure has a higher thermal conductivity coefficient than porcelain (Table 2). Due to greater surface area of metal collar at point B, points gets rapidly warmer or cooler when compared to point C. However, the metal substructure at point C was covered with porcelain and thus could not rapidly cool once it got warm. The thermal cycle generated by food consumption may further lead to cement failure at the buccal cervical third of a metal ceramic crown.

The results revealed that thermal stress levels were closely related to the temperature gradient. The cast gold post-core presented the lowest thermal stress values for cold stimulus. With high thermal conductivity, Type II gold conducted temperature evenly throughout the structure generating the lowest amount of compressive or tensile stress, due to lower thermal expansion coefficient and modulus of elasticity when compared to nickel-chromium.[17]

In cast nickel-chromium post and core, thermal conductivity coefficient was half of gold's. However, elasticity of modulus was three times greater than gold's therefore did not present an elastic behaviour as much as cast gold post-core. Hence, Type II gold may be recommended for single piece cast post-core fabrication.

The combination of amalgam core with stainless steel post generated the highest thermal stress value for hot stimulus in this study. The thermal expansion coefficient of amalgam is greater than nickel-chromium (Table 2). Even though, rapid warming and related expansion of amalgam core was anticipated, because of lower thermal expansion coefficient and higher modulus of elasticity, nickel-chromium substructure or prefabricated stainless steel post could not expand and generated thermal stress within the core and coronal one third of post.[21] This result was similar to previous studies by Asmussen et al.[19] and Yang et al.[10] The same thermal bevahiour may be considered for titanium post and amalgam core combination. Even though it must be validated by the results of in vivo and in vitro studies, it may be assumed that concentration of stresses at the interface of amalgam core and prefabricated metal post connection could lead to failure.

Composite resin has high thermal expansion coefficient when compared to amalgam but due to low thermal conductivity, it could not get warm rapidly and presented lower expansion or contraction and generated lower thermal stress values.[22,23] The metal posts in composite cores have higher modulus of elasticity and thus could not present elastic behaviour as much as composite resin.[17] This might have led to generation of thermal stress at post and core connection region. The results of the present study were in accordance with previous studies in terms of the relation between thermal conductivity and expansion coefficients.[15,20] The non-metal, fiber posts in composite cores might have acted more like analogous structures and generated lower thermal stress values.[24]

The von Mises stress levels in this study were higher than that reported by Yang et al.[10] which could be attributed to use of 3D model unlike 2D models used in the previous studies.[14] The reason for selecting von Mises criteria mostly depends on tensile type stresses. Güngör et al.[15] reported that brittle materials such as tooth, fail primarily to tensile type stresses.

This study evaluated the thermal stress related to thermal distribution by using 3-D FEA which has a complex structure that is affected by many factors. Other compounding variables such as mechanical loading during occlusion were not investigated. More complex numerical analyses supported by validation experiments are needed to confirm the findings and evaluate the combined effects of thermal changes and mechanical loading.

CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

- Different restorative materials may exhibit different stress distribution patterns for all post-core combinations.
- Single piece cast gold post-cores presented lower thermal stress values than two piece prefabricated post and core combinations.
- The temperature changes did not generate thermal stress on cortical bone, trabecular bone, periodontal ligament or gingiva.
- As cast gold post-core and non-metallic prefabricated post-composite core materials generated less thermal stress, their use in clinical practice could be recommended.

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