Original Article

Effect of Taper on Stress Distribution of All Ceramic Fixed Partial Dentures: a 3D-FEA Study

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Abstract:

Statement of Problem: Mechanical failure of ceramic materials is controlled by brittle fracture, mostly occurred in tension. In 3-unit all-ceramic FPDs the connector area is considered to be at fracture risk because of tensile stress concentrations.

Purpose: The aim of this FE analysis was to evaluate the effect of taper on stress distribution in all-ceramic FPDs.

Materials and Methods: In this experimental study two 3-D finite element models of thee-unit IPS-Empress 2 FPDs replacing mandible second premolar were created by means of finite element software. The digital images were obtained from CT scan of human skull. Abutment was reduced with 12 and 22 degrees of taper. The cement layer, PDL, cancellous bone and cortical bone were also modeled. Frameworks of core material were fabricated. A static load of 100 N was applied at mid pontic area. Resolved stresses were calculated according to the Von Mises criterion and principal stresses.

Results: In both models stresses were concentrated at the connectors. The maximum stresses were lower in the model with larger taper. The maximum Von Mises stress was recorded at the connector region of the premolar and the pontic. In model with larger taper the patterns of stresses were also more distributed and less concentrated.

Conclusion: The highest Von Mises and principal stress were recorded at the connectors. Tensile stresses developed at the gingival connector of premolar and pontic was higher than molar. The stress level in model with 22-degree taper was lower compare to 12-degree and the stress pattern was more distributed, lowered the risk of concentrations.

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Received: 28 December 2004
Accepted: 3 August 2005

Key Words: All ceramic crown; Finite element; Fixed partial denture

Journal of Dentistry, Tehran University of Medical Sciences, Tehran, Iran (2005; Vol: 2, No.3)

INTRODUCTION

As a result of the successful use of ceramic crowns and patient demands for esthetic and metal-free restorations, reinforced ceramic systems for fabricating fixed partial denture (FPD) were developed [1]. The performance of ceramic FPDs have assessed through several studies [2-5]. Steyren et al [2] reported a 90% success rate over 5 years. Sorenson et al [3] evaluated IPS-Empress 2 FPDs which were inserted over mean time of 12.1 month. Observed failure rate was 6.7 %. The survival rate of 100% for IPS-Empress2 crowns and 72.4% for 3-unit bridge of the same material over 3 years of service were reported by Zimmer et al [4]. Mechanical failure of ceramic material is almost completely controlled by brittle fracture, mostly occurred in tension [5]. In three- unit ceramic FPDs, the connector area is considered as a fracture risk factor, which can increase the tensile stress concentration under flexural compressive loading [6]. According to the law of beams when occlusal forces are applied directly through the long axis of an all-ceramic bridge connector, tensile stresses develop at the gingival surface of the connector. These stresses contribute to the propagating of micro cracks [7]. If the connector design is altered in regions where maximum tension occurs, the characteristic stress pattern can be optimized to improve the survival time of three-unit FPDs [8]. Pospiech et al [9] showed that stress concentration around connectors of bridges is reduced with connector of at least 4mm in height. Oh et al [8] demonstrated, by a finite element and a fractographic analyses, that the connector fracture was initiated at the gingival embrasure and that a larger radius of curvature at the gingival embrasure increased the fracture resistance of IPS-Empress 2 three-unit bridges. Oh and Anusavice [7] demonstrated the same in an in vitro study. It was shown that larger tooth preparation tapers or higher convergence angles usually resulted in a greater bulk of premolar crowns [11,12]. Tensile stresses in porcelain have also been reduced in all-ceramic crowns with thicker layer of material [13]. It was found that larger tapers in abutment preparation of FPDs could result in greater bulk of connector area and increased the overall strength of all-ceramic FPDs [14]. On the other hand the recommended angle of convergence for minimizing the stress in the cement layer is 2.5 to 6.5 degrees as optimum [15]. However at 20-degree, stress concentration was found to increase sharply [16]. Thus the aim of this study was to evaluate the effect of taper on stress distribution of all-ceramic FPDs. A finite element analysis was conducted through which principal and Von Mises stresses were measured. Briefly stated it may be shown that for any general point, o, in a body, there exist three perpendicular planes at o, on which the shear stresses vanish. The remaining normal stresses are called the principal stresses. The difference between maximum and minimum of principal stresses is a criterion of material yield. This difference should be smaller than two times the yield strength of material to prevent the yielding. There is another criterion which is more useful to predict failure. It is called Von Mises stress, that is the amount of normal stress causes the material to be distorted [17].

MATERIALS AND METHODS

Two 3-D finite element (FE) models of a three-unit IPS-Empress 2 fixed partial denture replacing mandibular second premolar were created on a Dell Precision 420 Dual-Pentium III, 1GHz (Dell Inc. Austin TX, USA) by means of finite element software ANSYS (ANSYS ver 7.1, Swanson Analysis Systems Co., Houston, TX, USA). To obtain digital files of human premolar and molar teeth a fully dentate, average size, male, human skull was chosen and CT images were digitally processed and exported to solid modeling software (Solid Work, full version 2003). The solid models were transferred into FEA program (ANSYS). The teeth served as abutments (first premolar and first molar) were prepared (volumetric reduction) following the recommended guidelines for full ceramic crown and bridge. Occlusal reduction of 1.5–2 mm from the central groove was performed. Minimum thickness of 0.8 mm for core material and rounded axial-gingival line angles were considered. All finish lines were placed in enamel. It was assumed that the enamel in the FE was removed and replaced by the ceramic material. Therefore underlying structure in the model was dentin. The pontic span was set to 7mm [18]. Angle of convergence of abutment preparations in first and second models was 12 and 22 degrees respectively. The FPDs of IPS-Empress 2 core materials were designed so that the dimensions of connector area in two bridges were 4mm in height and 4mm in width [19] .The radius of curvature of the gingival embrasure of connectors was set to 0.9 mm. The cement layer was modeled with minimum thickness of 25 µm. Each model included elements for normal tooth structure, the periodontal ligament, cancellous bone and cortical bone. All structures were presumed linear elastic, homogenous and isotropic [9,20,21]. The characteristic material values such as elastic modulus and Poisson's ratio were used based on published data [22] and are summarized in Table I.

Table I: Materials properties used in this study.

Material	Elastic Modulous (GPa)	Poission's Ratio
Dentine	17.6	0.25
PDL	0.027	0.45
Cortical Bone	14.7	0.3
Cancellous Bone	0.49	0.3
Luting Composite (Variolink Π)	8.3	0.24
Lithium disilicate Glass ceramic (IPS Empress 2)	96	0.25

The 3-D models were meshed with approximately 80,000 structural solid four-node tetrahedral elements and 140,000 nodes. The models were re-meshed with a finer mesh to increase the accuracy of the stress and reliability of calculations (Fig.1). A simulated static load of 100 N [8] was applied at the central fossa of the pontic, to induce maximum bending stress in the prostheses. The load was distributed uniformly and at right angle of occlusal surface. Resolved stresses were calculated according to the Von Mises criterion [6] and principal stresses [8,22]. Stresses were also examined at specific points

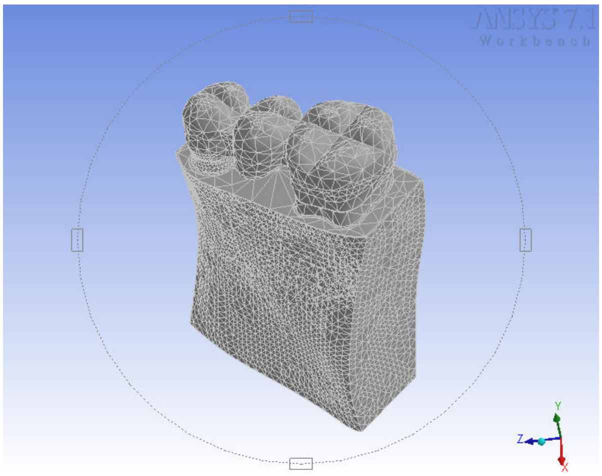

Fig1: Finite element model with all-ceramic bridge design used for this study

of interest within each model.

RESULTS

The resolved stresses of Von Misses and principal for two models are summarized in Table II and III. For two models, stresses were concentrated at the connector areas (Fig.2). Two sites of sever principal stress concentration were identified. Peak compressive stresses occurred at the occlusal embrasure, and peak tensile stresses developed at the gingival embrasure, either at the center or at a position near to the pontic (Fig 3). Maximum stresses in the connector area, were lower with the larger occlusal convergence angle (model II, 22 degrees). In model I (12 degrees), stress levels were higher in the premolar and showed 30% increase in the occlusal embrasure. The maximum Von Mises stress was recorded for the connector region of the premolar and the pontic, at 25 MPa. The peak principal stress resolved at 21 MPa. The maximum Von Mises strain in the same region was 0.05. The patterns of stress distributions were approximately the same for model II (22 degrees). The stress however showed more distributed and more favorable patterns. In model II the peak Von Mises stress and the

Table II: Maximum von-mises stresses in Mpa

Taper	bridge	First premolar	First molar	PDLof First premolar	PDL of First molar	bone
12	25	7	4	1.4	1.1	1.3
22	20	7	3.7	1.4	1.1	1.3

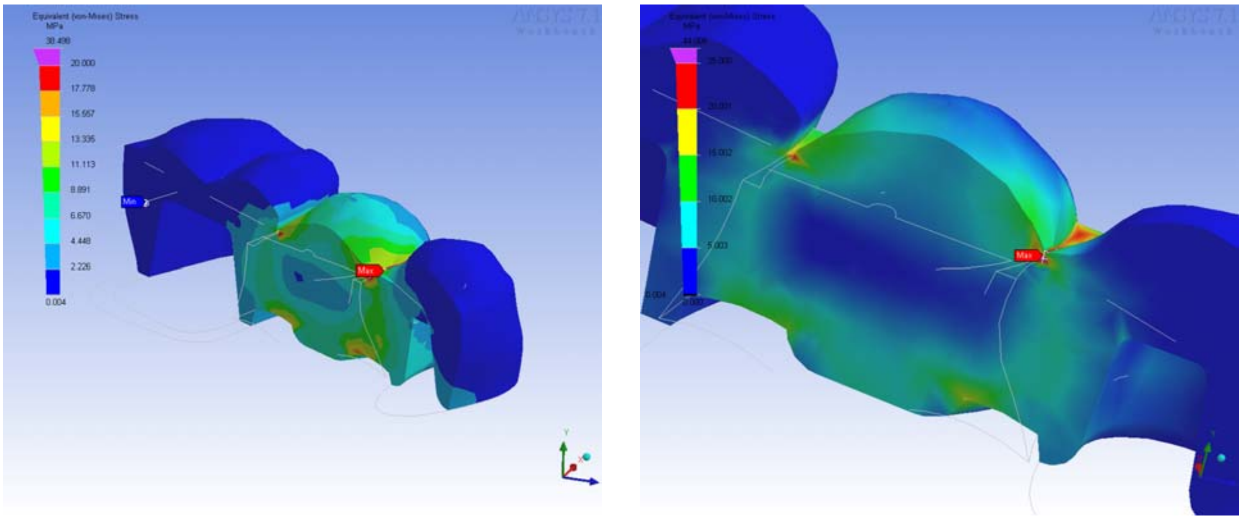

Fig. 2: Von Mises Stress-distribution of model 1 (left) and model 2 (right).

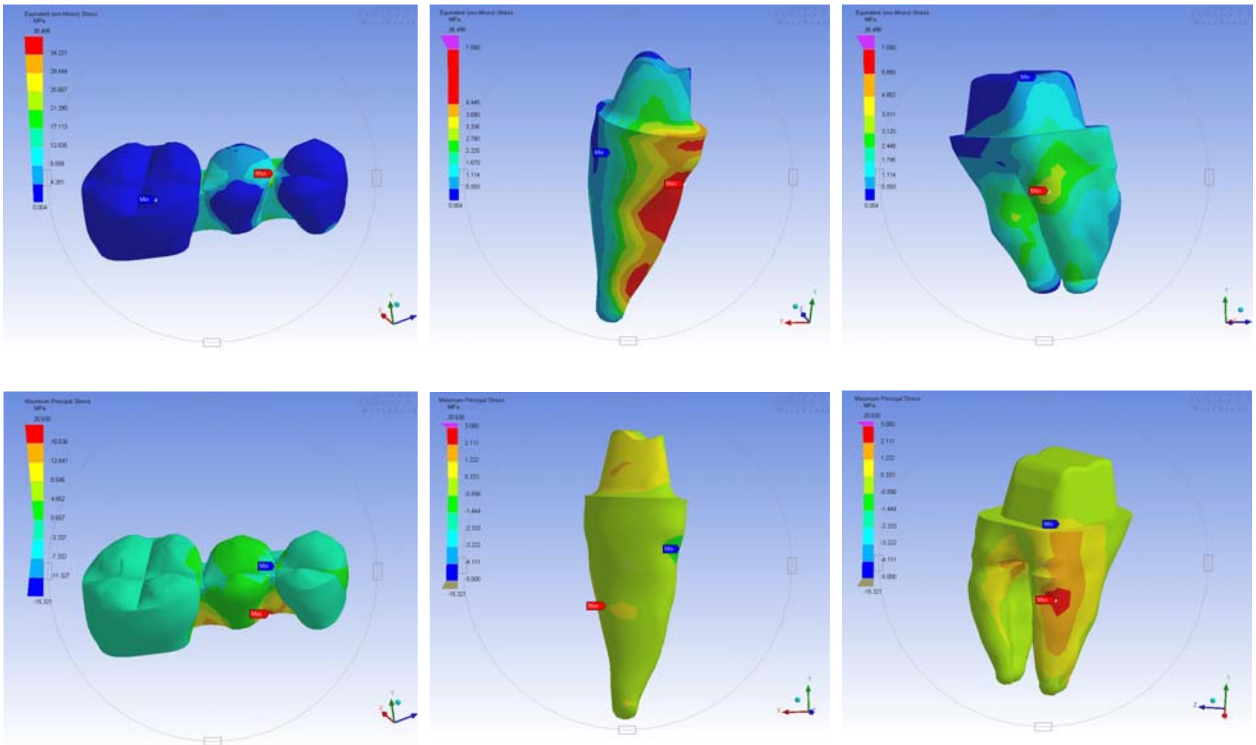

Fig. 3: Von Misses stress distribution (top) and principal stresses (bottom) on model 1 with in bridge (left) first premolar (middle) and first molar (right)

Table II: Maximum principal stresses in Mpa

Taper	bridge	First premolar	First molar	PDLof First premolar	PDL of First molar	bone
12	21	1.7	2.66	1.2	0.7	0.7
22	19	1.6	2.44	1.2	0.7	0.7

maximum principal stress showed 20 % (20 MPa) and 9.5 % (19 MPa) reduction respectively. The peak tensile stress developed in the connector region of the premolar and the pontic were similar to model I.

For the adhesive cement layer, the tooth structure, PDL, and bone, slight differences were evident for the two models.

DISCUSSION

The connectors showed the weakest point of the models in this study which is in agreement with the previous studies [3,23].The stress behavior in the FE models of the present study is consistent with the fractographic analysis of other studies [8] in which failure origin of 3-unit ceramic prostheses occurred at the gingival embrasure. In both models (12 and 22 degrees) the gingival connector between premolar and pontic revealed the peak intensity of stresses. This behavior may be caused by the less cross section of the area. Maximum principal stress in the connector area of the FPDs in two models are about 20–25 MPa, which are far smaller than characteristic strength values published in previous studies at 290 MPa [22] (Fig.3). This indicates that short-term loadings can not be responsible for failure. The long term aspects as well as statistical effects (eg Weibull analysis) influence the risk for failure and should be taken into account which did not studied here. Two values of convergence, 12 and 22 degrees, were selected for the models in this study. Minimal tooth taper has been regarded as an essential factor in retention of indirect cast metal [24]. The literature reviews as well as clinical experiences however indicate the small angle of convergence is usually not achievable clinically [25]. Poon et al [26] and Smith et al [27] supported single crown convergence angle to be from 12 to 20 degrees. Optimum taper ranges from 14 degrees on premolars to 24 degrees on molars [15]. Therefore the two tapers of 12 and 22 were used in order to keep the practical limits. In the present study a vertical force of 100 N was applied at the mid-pontic area and produced a compressive stress within the prostheses at the occlusal embrasure and a tensile stress distribution at the gingival embrasure corresponding to the beam model [7, 28]. The models were computed with a 100 N applied force which is equal to average bite force. In other study maximum bite force of 600 N was applied [22]. The aim of this study was not to determine the strength or load-to-failure of the FPDs, but to evaluate the stress distribution. Hence the applied load will not affect the major findings of this study. In addition minimum thickness of cement layer was considered in the study models. Effect of cements with different elastic modulus on stress distribution in intracoronal bonding restorations was studied by Ausiello et al [29]. Other studies, however demonstrated that the effect of cement on stress and strain in tooth or prosthesis are negligible when the aim is to compare models [30].

The results of this study favored the larger taper of abutments of all-ceramic FPDs. The stress showed more distributed pattern in 22-degree model. It is however should not interpreted as a recommendation for larger taper in all clinical situations. Based on the literatures, several factors influence the failure of all-ceramic FPDs. The in vitro and clinical fracture resistance of ceramic FPDs is related to the size, shape and position of the connector and to the span of the pontic [1]. The magnitude and duration of loads and the nature of supporting structures also are believed to affect the strength of all-ceramic prosthesis [31]. The results of different in vitro studies should however, be validated by well-designed clinical trials [32]. It is the clinician's task to consider the risk factors and tailor the treatment options individually.

CONCLUSION

Based on this FEA in all-ceramic FPDs, the following conclusion could be drawn:

-The highest Von Mises and principal stress were recorded at the connectors

-Tensile stresses developed at the gingival connector of premolar and pontic was higher than molar.

-The stress level in abutment with 22-degree taper was lower in comparison with 12-degree model and the stress pattern was more distributed, lowered the risk of concentrations.

REFRENCES

1- Raigrodski AJ, Chiche GJ. The safety and efficacy of anterior ceramic fixed partial dentures: A review of the literature. J Prosthet Dent .2001 Nov;86(5):520-5. Review

2- Vult Von Styrene P, Jonsson O, Nilner K. Five year evaluation of posterior all-ceramic three-unit (In-Ceram) FPDs. Int J Prosthodont. 2001 Jul-Aug;14(4):379-84.

3- Sorensen JA, Cruz M, Wayne TM, Raffeiner O, Meredith HR, Foser HP. A clinical investigation on three-unit fixed partial dentures fabricated with a lithium disilicate glass-ceramic. 1999 Jan-Feb;11(1):95-106; quiz 108.

4- Zimmer D, Gerds T, Strub JR. Survival rate of IPS-Empress 2 all-ceramic crowns and bridges: three years results. Schweiz Monatsschr Zahnmed 2004;114(2):115-9. German

5- Seghi RR, Sorensen JA. Relative flexural strength of 6 ceramic materials. Int J Prosthodont 1995;8: 239-46

6- Komposiora Ph, Papavasiliou G, Bayne SC, Felton DA. Stress concentration in all-ceramic posterior fixed partial dentures. Quintessence Int 1996 Oct;27(10):701-6.

7- Oh WS, Anusavice KJ. Effect of connector design on the fracture resistance of all-ceramic fixed partial dentures. J Prosthet Dent . 2002 May;87(5):536-42

8- Oh W,Gotzen N,Anusavice KJ. Influence of connector design on fracture probability of ceramic fixed partial dentures. J Dent Res 2002 Sep;81(9):623-7

9- Pospiech P, Goldhofer G, Gernet W. All-ceramic resin-bonded bridges A 3-dimensional finite-element analysis study.. Eur J Oral Sci 1996 Aug;104(4 (Pt 1)):390-5.

10- Sorensen JA, Kang SK, Roumanas E, Avera SP. Effect of preparation design on flexural strength of all-ceramic bridges. J Dent Res 1991; 70: 471 (Abst 1642)

11- Chitmongkolsuk S, Heydecke G, Stappert Ch, Strub JR. Fracture strength of all-ceramic lithium disilicate and porcelain fused-to-metal bridges for molar replacement after dynamic loading. Eur J Prosthodont Rest Dent 2002; 10(1):15-22

12- Doyle MG, Goodacre CJ, Munoz CA, Andres CJ. The effect of tooth preparation design on the breaking strength of Dicor crowns: part II. Int J Prosthodont 1990 Jul-Aug;3(4):327-40.

13- Anusavice KJ, Hojjatei B. Tensile stress in glass-ceramics: effect of flaws and cement voids. Int J Prosthodont 1992;5(4):351-8.

14- Sadighpour L. Efeect of angle of convergence of abutments on fracture ressitance of three-unit fixed partial denture fabricated with IPS-Empress 2.[dissertation].Tehran University of Medical Science;2003

15- Shillinburg HT, Hobo S, Whitsett LD, Jacobi R, Brackett SE. Fundamentals of fixed prosthodontics, third edition, Quintessence Publishing Co,1997.

16- Magne P, Perakis N, Besler UC, Krejci I. Stress distribution of inlay-anchored adhesive fixed partial dentures: a finite element analysis of the influence of restorative materials and abutment

preparation design. J Prosthet Dent 2002 May;87(5):516-27.
17- Boresi AP, Schmidt RJ, Side bottom OM. Advance mechanics of material. 5th edition. 1993, John Wiley & sons
18- Artola M. Space analysis in fixed partial prosthodontics- normal parameters. Compend Contin Educ Dent 2002 Jan;23(1):11-4, 16-8.
19- Sorensen JA. The IPS-Empress 2 system: Defining the possibilities. QDT 1998; 22:153-163
20- Augereau D, Pierrisnard L, barquins M. Relevence of the finite element method to optimize fixed partial denture design. Clin Oral Invest 1998 Mar;2(1):36-9
21- Gungor M A, Kucuk M, Dundar M, Karaoglu C, Artunc C. Effect of temperature and stress distribution on all ceramic restorations by using a three- dimensional finite element analysis. J Oral Rehabil 2004 Feb;31(2):172-8
22- Fischer H, Weber M, Marx R. Lifetime prediction of all-ceramic bridges by computational methods.J Dent Res 2003 Mar;82(3):238-42
23- Kelly JR, Tesk JA, Sorensen JA. Failure of all-ceramic fixed partial dentures in vitro and in vivo: Analysis and modeling.J Dent Res 1995 Jun;74(6):1253-8.
24- Kaufman EG, Coelho DH, Laurence C. Factors influencing the retention pf cemented gold castings. J Prosthet Dent. 1961; 11:487-502
25- Mack PJ.A theoretical and clinical investigation into the taper achieved on crown and inlay preparation. J Oral Rehabilit 1980 May;7(3):255-65.
26- Poon BK,Smales RJ. Assessment of clinical preparations for single gold and ceramometal crowns. Quintessence Int. 2001 Sep;32(8):603-10.
27- Smith ChT,Gary JJ, Conkin JE, Franks HL. Effective taper criterion for the full veneer crown preparation in preclinical prosthodontics. J Prosthodont 1999 Sep;8(3):196-200.
28- Anusavice KJ. Philips's science of dental materials,10th ed, Philadelphia: WB Saunders, 1996.
29- Ausiello P, Rengo S, Davidson CL, Watts D C. Stress distribution in adhesively cemented ceramic and resin-composite class II inlay restorations: a 3D study. Dent Mater 2004; 20: 862-872.
30- Abu-Hassan ML, Abu-Hammad, Harrison A. Stress distribution associated with laoded ceramic onlay restorations with different designs of marginal preparation. An FEA study. J oral rehabil 2000;27:294-298.
31- Rosentritt M, Plein T, Kolbeck C, Behr M, Handel G. In vitro fracture force and marginal adaptation of ceramic crowns fixed on natural and artificial teeth. Int J prosthodont 2000;13: 387-391
32- Kelly JR. Clinically relevant approach to failure testing of all-ceramic.

اثر میزان تقارب تراش بر توزیع تنش در پروتزهای پارسیل ثابت تمام سرامیکی به روش آنالیز اجزای محدود سه بعدی.

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چکیده

بیان مسأله: شکست مکانیکی در رستوریشن‌های تمام سرامیکی توسط مکانیسم شکست brittle کنترل می‌شود. بـه نظـر مـی‌رسـد در رستوریشن‌های سه واحدی تمام سرامیک، ناحیه اتصال (کانکتور) به دلیل تجمع تنش کششی در معرض خطر شکستن باشد.

هدف: هدف از این مطالعه آنالیز اجزای محدود، تعیین اثر میزان تقارب در توزیع تنش در پروتزهای پارسیل ثابت تمام سرامیکی است.

روش تحقیق: در این مطالعه تجربی، دو مدل سه بعدی رستوریشن سه واحدی تمام سرامیک، جهت جایگزینی پره‌مولر دوم فک پـایین با استفاده از نرم‌افزار finite element طراحی شد. تصاویر دیجیتالی از سی‌تی‌اسکن جمجمه انسان تهیه شد. پایه‌ها بـا دو درجـه تقـارب مختلف ۱۲ و ۲۲ درجه تراش داده شدند. لایه سیمان دندان، لیگامان‌های پریودنتال، استخوانهای اسفنجی و کورتیکال نیز بازسازی شدند. چهارچوبهای (framework) ماده کور (core) تهیه گردید. نیروی استاتیک ۱۰۰ نیوتن به ناحیه میانی پونتیک وارد شد. نتایج بر اسـاس von mises criterion و تنش‌های principal بررسی شدند.

یافته‌ها: در هر دو مدل، تنش در ناحیه اتصال تجمع یافته بود. حداکثر تنش در مدل با تقارب بالاتر، کمتر از مدل دیگر بود. حداکثر تنش von mises در ناحیه اتصال پایه پره‌مولر و پونتیک بود. در مدل با تقارب بیشتر، توزیع تنش با انتشار بیشتر و تراکم کمتری همراه بود.

نتیجه‌گیری: حداکثر تنش von mises و principal در هر دو مدل، در ناحیه اتصال دیده شد. تنش کششی در ناحیه لثه‌ای پره‌مـولر و پانتیک بیشتر از دندان پایه مولر بود. سطح تنش در نمونه با تقارب ۲۲ درجه کمتر از ۱۲ درجه بود و الگـوی تـنش در تقـارب ۲۲ درجـه منتشرتر بود که احتمال تجمع تنش را کاهش می‌دهد.

واژه‌های کلیدی: روکش‌های تمام سرامیک؛ آنالیز اجزای محدود؛ رستوریشن‌های پارسیل ثابت

مجله دندانپزشکی دانشگاه علوم پزشکی و خدمات بهداشتی, درمانی تهران (دوره ۲, شماره ۳, سال ۱۳۸۴)