

Effects of occlusal load on the cervical stress distribution: A three-dimensional finite element study

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ABSTRACT

The objective of this study was to investigate the effects of various occlusal loads on the stress distribution of the buccal cervical region of a normal maxillary second premolar, using a three dimensional finite element analysis (3D FEA).

After 3D FE modeling of maxillary second premolar, a static load of 500N of three load cases was applied. Stress analysis was performed using ANSYS (Swanson Analysis Systems, Inc., Houston, USA). The maximum principal stresses and minimum principal stresses were sampled at thirteen nodal points in the buccal cervical enamel for each four horizontal planes, 1.0 mm above CEJ, 0.5 mm above CEJ, CEJ, 0.5 mm under CEJ.

The results were as follows

1. The peak stress was seen at the cervical enamel surface of the mesiobuccal line angle area, asymmetrically.
2. The values of compressive stresses were within the range of the failure stress of enamel. But the values of tensile stresses exceeded the range of the failure stress of enamel.
3. The tensile stresses from the perpendicular load at the buccal incline of palatal cusp may be shown to be the primary etiological factors of the NCCLs. [J Kor Acad Cons Dent 31(6):427-436, 2006]

Key words: Occlusal load, Stress distribution, Finite element analysis, Maxillary second premolar, Compressive stress, Tensile stress

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I. INTRODUCTION

The loss of hard tissue in the cervical region of the tooth is a common clinical occurrence¹⁾. These noncarious cervical lesions (NCCLs) can occur on facial, lingual and/or interproximal surfaces.

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Traditionally, this has been assumed to be due to the effects of abrasion and/or erosion¹⁻³⁾. More recently, an additional mechanism for cervical tooth loss with occlusal loading has been proposed^{2,4)}. Grippo³⁾ has coined the term "abfraction" to distinguish it from lesions caused by erosion and abrasion.

Clinically, there is some clinical evidence for the association of abfraction lesions with heavy occlusal loads. There is a marked association of these lesions with bruxism and malocclusion⁵⁾. Some epidemiologic studies also reported a strong association between cervical lesions and occlusal tooth wear or occlusal erosion with 96% of teeth with a cervical lesion also having evidence of occlusal pathology⁶⁾. These lesions have been shown in teeth subjected to lateral load, but adjacent teeth that were not subjected to these forces remained unaffected⁷⁾.

Abfraction lesions are sharp, angular, wedge-shaped defects that sometimes have a subgingival location and are often associated with occlusal wear facets⁷⁻⁹⁾. These lesions are commonly observed on the buccal and labial aspects of the teeth. These lesions were rarely found on the lingual surface with one study reporting that only 2% of cervical lesions were found lingually⁶⁾.

There is a gradually increasing body of evidence to suggest that the effects of occlusal loading contribute to the development of abfraction lesions. This evidence comes from various types of stress and strain analysis including photoelastic stress analysis, strain gauge studies and finite element analysis (FEA).

Selna and co-workers¹⁰⁾ revealed through 2D FEA that eccentric load application demonstrated internal stress distribution in the crown and roots, which may be interpreted as possible failure planes both in the dental structures and restorations. Yettram and co-workers¹¹⁾ showed that the occlusal load on a mandibular second premolar flowed around enamel cap and through the thin enamel cervical area before being transmitted to the root in their 2D FEA. Goel *et al.*¹²⁾ used the 3D FE model of the maxillary first pre-

molar. The magnitude of normal stresses increased at the cervical enamel and the normal stress and shear stress were markedly affected by the contour of the dentinoenamel junction (DEJ) and the thickness of the occlusal third on the buccal and lingual surfaces.

Palamara *et al.*¹³⁾ used the model 3D FEA of a mandibular second premolar to investigate the effects of occlusal load on enamel surface. Point loads of 100N were applied axially at the 45° from the vertical at the cusp. Strains predicted from the FEA model were in excellent agreement with the strain gauge measurements. Strains were concentrated near cemento-enamel junction (CEJ) regardless of load direction. Rees¹⁴⁾ developed 2D FEA of a maxillary incisor, canine and first premolar and the cervical stress profiles were examined along a horizontal plane 1.1 mm above the CEJ. The result of 500 N loaded 45° labioapically to the incisal tip was that the stress profile in the cervical region of central incisor was greater than the canine or premolar. Tanaka *et al.*¹⁵⁾ carried out stress analysis on the upper central incisor and the lower first molar using the plastic-elastic deformation theory with 2D FEA. The result was that oblique loading causes plastic deformation near the CEJ. Geramy and Shara-foddin¹⁶⁾ developed 3D FEA of a maxillary central incisor including periodontal ligaments and alveolar bone, which was loaded 1.5 N static non-axial and axial loads on the palatal side. The maximum displacement and stresses were shown at the cervical area on the non-axial load, but the axial load did not show the same.

In the previous study of 2D FEA, the results are unreliable for assessment of stress patterns due to its inability to duplicate tooth geometry. Further refining the 3D FE model shape was important when analyzing the stress distribution within a tooth. The objective of this study was to investigate the effects of various occlusal loads on the stress distribution of the buccal cervical region of a normal maxillary second premolar, using a 3D FEA.

II. MATERIALS AND METHODS

Finite element model

For developing a 3D FE model to analyze, an intact normal extracted human maxillary second premolar was selected in this study. The premolar was scanned serially with Micro-CT (SkyScan 1072; SkyScan, Aartselaar, Belgium) to exposure the tooth sections perpendicular to the long axis of the tooth (58 μm in thickness) and parallel to the occlusal plane. 3D-DOCTOR (Able Software Co., Lexington, MA, USA) image processing software was employed to detect the boundaries of enamel, dentin and pulp from the sectioned two dimensional images and to make a three-dimensional surface model. Rhino 3D (Robert McNeel & Assoc., Seattle, WA, USA) was used to reduce useless nodes from the surface model and ANSYS (Swanson Analysis Systems, Inc., Houston, USA) was used to mesh.

The 3D FE model was consisted of hexahedral elements. The final model consisted of 15,608 elements with 17,052 nodes. All the vital tissues were presumed linearly elastic, homogeneous and isotropic. The corresponding elastic properties such as Young's modulus and Poisson's ratio were determined according to literature survey (Table 1).

The periodontal ligament was assumed to be 0.3 mm wide, and the dimensions of surrounding

compact and cancellous bone were derived from standard texts^{18,19}. The alveolar bone was also generated by growing the outer surface of the tooth model from 2 mm below the CEJ^{18,19}. The pulp region was modeled as being hollow²⁰. In these models, the outer surface of the alveolar bone model was fixed in order to prevent rigid body motion for FEA.

The model was fixed on mesiodistal direction. In all loading cases, the base nodes of simulated alveolar bone were assumed fixed to prevent rigid body motion.

Loading conditions

Static 500 N forces were applied for the following three loading conditions (Figure 1). The eccentric occlusion was simulated with two loading conditions. Load-I represented the perpendicular load at the point of upper third of palatal incline of buccal cusp. Load-II represented the perpendicular load at the point of upper third of buccal incline of palatal cusp. And the centric occlusion was simulated with Load-III. Load-III represent a unit load distributed at the three points corresponding to centric occlusion (A: perpendicular load on the lower third of palatal slope of buccal cusp, B: perpendicular load on the buccal slope of palatal cusp, C: perpendicular load on the center of mesial marginal ridge).

Table 1. Mechanical properties of the materials used in the study

Materials	Mechanical properties	
	Young's modulus (MPa)	Poisson's ratio (ν)
Enamel	84000 ^a	0.33 ^a
Dentin	18000 ^a	0.31 ^a
PDL	0.667 ^b	0.49 ^b
Cancellous bone	13700 ^b	0.38 ^b
Cortical bone	34000 ^b	0.26 ^b

a : Katona *et al.*¹⁷ b : Geramy *et al.*¹⁶

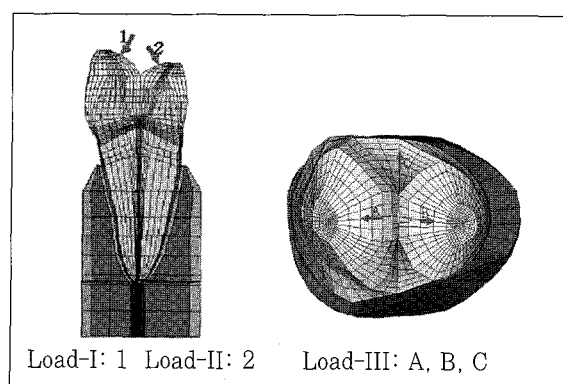


Figure 1. Three load conditions of 3D FE model.

Stress analysis

Analysis of the principal stresses has been done by ANSYS.

The values of maximum and minimum principal stresses of thirteen nodal points in the buccal cervical region were sampled along four horizontal surface enamel planes (Level A, B, C, and D) and two horizontal DEJ planes (Level A, B). The Level of CEJ was designed as Level C and which was used as reference plane. Level A and B were the plane of 1.0 mm and 0.5 mm above the CEJ level, respectively. And the Level D was 0.5 mm below the CEJ.

III. RESULTS

Principal stress analysis

Cervical stress contours on the tooth surface in response to a static point 500 N load are shown in figure 2.

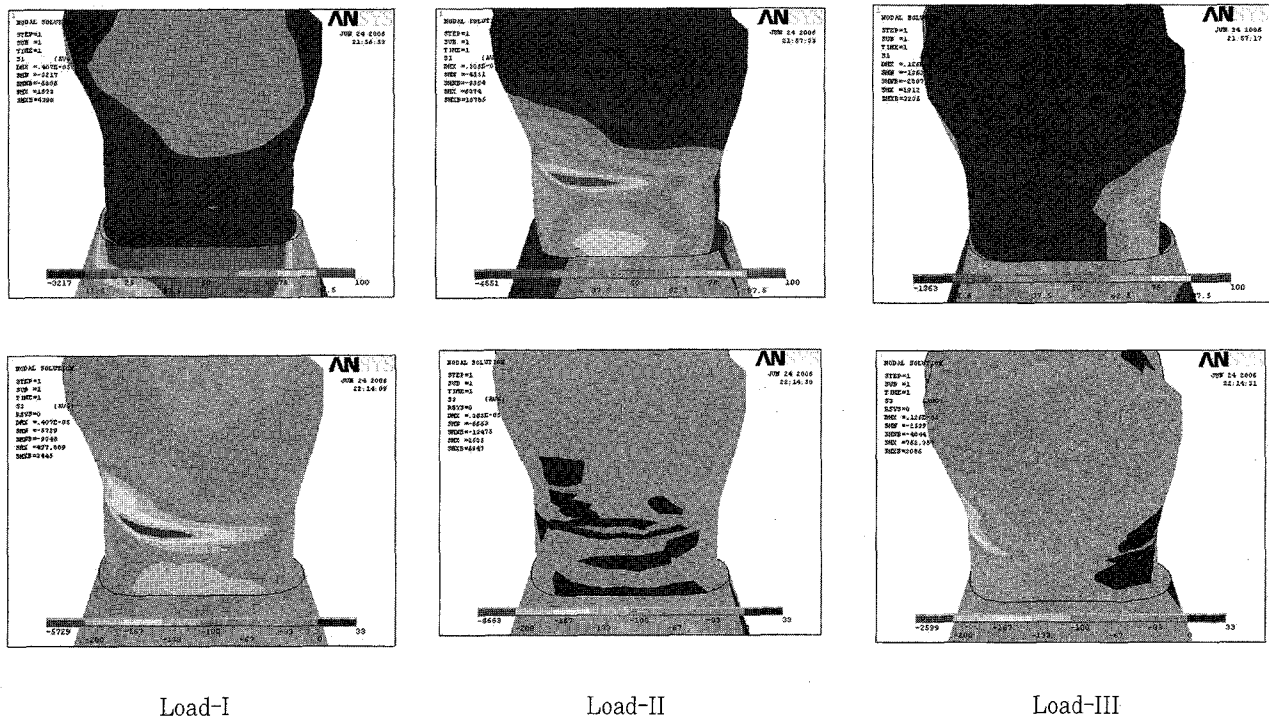
The principal stresses of Level A (Figure 3)

The principal stresses were different in magnitude and character according to the load conditions.

In Load-I case, the peak tensile stress of 17 MPa at the mid-buccal and the peak compressive stress over the 144 MPa at the mesial side were observed. But in Load-II case, the peak tensile stress of 49 MPa was concentrated at the mesiobuccal line angle area. And in Load-III case, tensile stress of 21 MPa at the distal side and the peak compressive stress of 121 MPa at the mesial side were observed.

The principal stresses of Level B (Figure 3)

Peak compressive stress of 152 MPa was concentrated at the mesiobuccal line angle area in Load-I case. And peak tensile stress of 59 MPa at the mesiobuccal line angle area in Load-II case. In Load-III case, peak compressive stress of 118



Load-I

Load-II

Load-III

Figure 2. Principal stress distribution of Load-I,II,III
(Upper lines: tensile stress distributions Lower lines: compressive stress distributions).

MPa at the mesiobuccal line angle and peak tensile stress of 32 MPa at the distobuccal line angle were detected.

The principal stresses of Level C (Figure 3)

In Load-I case, the peak tensile stress of 20 MPa at the distal side and the peak compressive stress over the 226 MPa at the mesiobuccal line

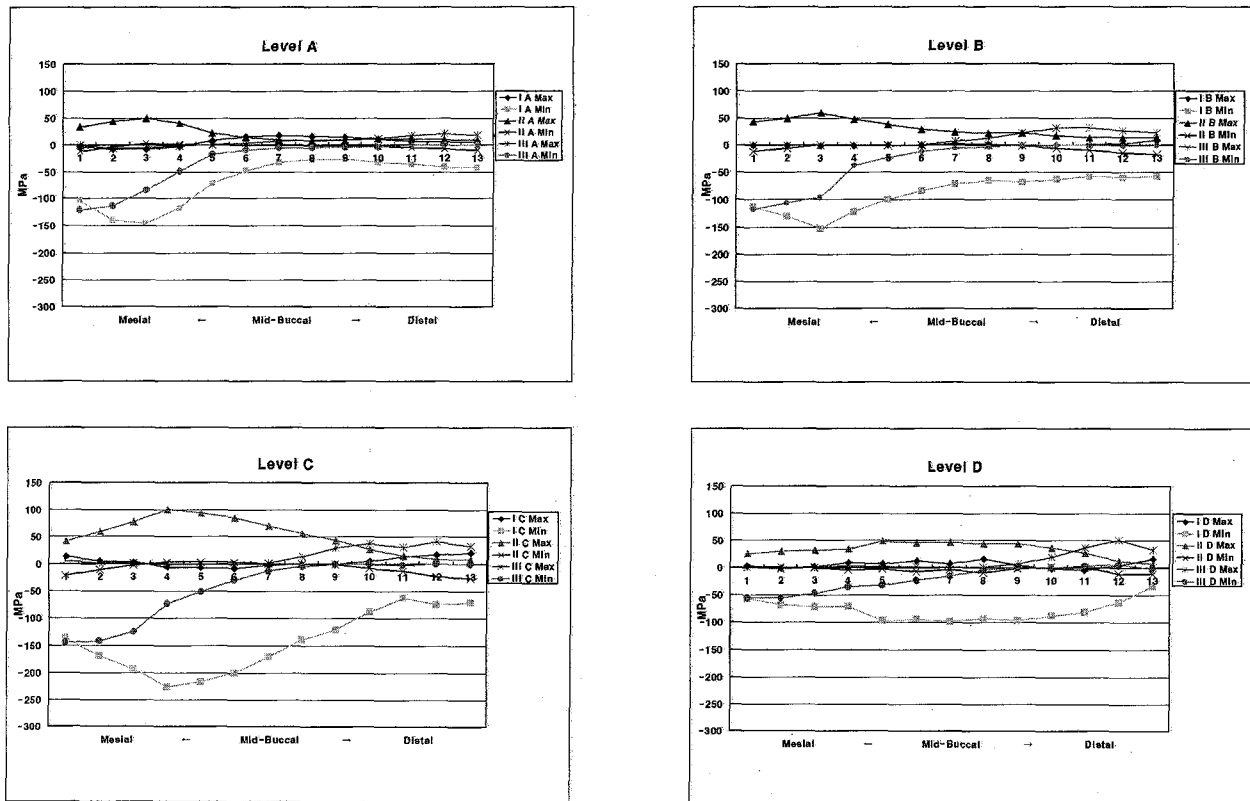


Figure 3. Principal stresses of Level A,B,C,D of three load conditions.

Table 2. Peak stresses of enamel surface of various levels and loading points

		Load I		Load II		Load III	
		MPa	Node	MPa	Node	MPa	Node
Level A	Max	17*	7	49*	3	21*	12
	Min	-144	3	NS	NS	-121	1
Level B	Max	NS	NS	59*	3	32*	11
	Min	-152	3	NS	NS	-118	1
Level C	Max	20*	13	101*	4	41*	12
	Min	-226	4	NS	NS	-144	1
Level D	Max	16*	8	49*	5	51*	12
	Min	-97	5	NS	NS	-55	1

*: Excessive stresses over the failure range, NS: Not significant

Table 3. Mechanical properties of teeth (MPa)*

Compressive strength of enamel	277 - 384
Compressive strength of dentin	249 - 347
Tensile strength of enamel	10 - 24
Tensile strength of dentin	32 - 103
Tensile strength of dentinoenamel junction	52

* Litonjua *et al.*²¹⁾

angle area were observed. But in Load-II case, the peak tensile stress over the 101 MPa was concentrated at the mesiobuccal line angle area. And in Load-III case, the tensile stress was particularly observed between the mid-buccal and the distal CEJ. The peak tensile stress of 41 MPa at the distal CEJ and the peak compressive stress of 144 MPa at the mesial CEJ were observed.

The principal stresses of Level D (Figure 3)

In Load-I case, the peak tensile stress of 51 MPa at the distal root surface dentin and the peak compressive stress over the 97 MPa at the mesiobuccal line angle area were observed. But in Load-II case, the peak tensile stress of 49 MPa was observed at the mesiobuccal line angle area. And in Load-III case, the peak tensile stress of 51 MPa at the distal root surface dentin and the peak compressive stress of 55 MPa at the mesial side were observed.

For the convenience of analyzing the overall stress distribution of enamel surface, the peak stresses of four levels according to load conditions were summarized in Table 2 and compared to mechanical properties of tooth structure (Table 3).

IV. DISCUSSION

The etiology of NCCLs has not been precisely defined. Most authorities agree that the cause is multifactorial and thus difficult to recognize²²⁾. The most frequent causes are erosion, abrasion and occlusal loading. Occlusal stresses are the primary cause in traumatic occlusion and bruxism

can produce cervical lesions²³⁾. When eccentric occlusal forces are applied to a tooth, both compressive and tensile stresses are placed on the structure. The stress produced causes the tooth to flex. This has been proposed as a tooth flexure theory by Levitch *et al.*²⁴⁾. The fulcrum of this bending movement and the place where eccentric occlusal forces are concentrated is the cervix of the tooth. The location of the fulcrum determines the exact site of the lesion²⁴⁾. A longitudinal case study²⁵⁾ of a person showed a direct correlation between occlusal wear and the growth of NCCLs. Heymann *et al.*²⁶⁾ also found a relationship between the loss of cervical restorations and the presence of a traumatic occlusion, which is expected to cause more cuspal flexure.

In order to determine the load conditions such as magnitudes, directions, occlusal contacts (i.e., point or surface, centric or eccentric), preliminary investigation was performed using the data gathered by literature review^{27,28)}. Based upon these data, 170 N was assumed as the chewing force for premolars and 500 N was assumed as the heavy parafunctional load of bruxism and traumatic occlusion. In this study, a tooth model loaded by a point load of static 500 N was considered more representative of high-risk loading situation, in contrast to other FEA studies¹¹⁻¹⁶⁾. Load-I for buccal eccentric occlusion and Load-II for palatal eccentric occlusion were selected. Load-III was selected for mimicking the effect of a unit load in centric occlusion.

The peak stress was seen asymmetrically at the CEJ of mesiobuccal line angle area. The position of maximum stress concentration found in this study was different from previous studies²⁹⁻³²⁾. This pattern of stress distribution may be related to the anatomical asymmetry. Palamara *et al.*¹³⁾ reported that strains resulting from oblique loads on buccal cusp inclines were asymmetric.

The position of the peak stress found in this study was at the CEJ. Many studies^{11,13,15,16,29-31)} reported that the peak stress was concentrated at the CEJ in their FEA models. Kuroe *et al.*³²⁾ also confirmed by the photoelastic method that a vertical force loaded on the tooth causes stress con-

centration at the cervical line.

Contrary to our results, Rees *et al.*^{4,14,33-35} proposed that the sampling horizontal planes were chosen at 1.1 mm above the CEJ among the buccal cervical region because an initial pilot study showed this to be the position of maximum stress concentration. Despite their findings, the results of their study must be interpreted with a certain amount of caution. First, their analysis was a 2D FEA so it was not possible to model any small twisting movements of the tooth in the Z-axis direction. Second, their study modeled a buccolingual slice through the center of the tooth and therefore represents the worst possible case, since they assumed that teeth flex more in the middle. They thought that a more mesially or distally placed slice would give less cuspal flexure and, presumably, lower cervical stresses. However, in our study, mesiobuccal line angle area was greater than mid-buccal area under 3D FEA model.

Several studies have shown that enamel and dentin are less resistant to tensile stress than compressive stress³⁶⁻³⁹. In compressive stress, enamel can withstand forces up to 35 times greater than when subjected to tensile stress; meanwhile, dentin can resist compressive forces at least seven times greater than the amount of tensile stress that will cause it to fail^{37, 38}. The tensile strengths of enamel and dentin are much lower than are their respective compressive strengths^{38,39}.

According to the experiment, tensile stress affected the result to the meaningful level while the effect of compressive stress was not. For in terms of Level A, B, C, and D, the peak compressive stress was under the failure stress of the enamel but the peak tensile stress observed 4 times as much as the failure stress of the enamel.

As the results of the evaluation of the principal stresses, it has been shown that the tensile stress on the buccal CEJ regions was dominant in the lesion initiation. This results are similar with Tanaka *et al.*¹⁵ which they reported that when the force was oblique, plastic deformation of the lower first molar appeared at the enamel surface

along the cervical region because of the tensile stress. Spears *et al.*⁴⁰ showed that a vertical force loaded at one tip of the lingual cusp of the mandibular second premolar produces tensile stress at the lingual enamel on the cervical region. Borcic *et al.*³¹ reported that in their 3D FEA model, large tensile stress appeared on the enamel surface near the cervical line at the side opposite the loading point.

This study reports a strong association between loading forces of Load-II and the possibility of failure of enamel and dentin of the buccal cervical area by tensile stress -the same as other studies^{15,29,31}. Since the tensile stress of Load-II was 101 MPa, the highest level on the CEJ, Load-II is thought to be the most damaging factor. Lee and Eakle⁷ also proposed that the primary etiologic factor in wedge-shaped cervical lesions is tensile stress from mastication and malocclusion, and that local factors may play a secondary role in the dissolution of tooth structure.

We adopted Load-III mimicking centric occlusion as control group in order to compare it with the eccentric occlusion. Unexpectedly, Load-III generated tensile stress enough to destroy enamel on the distal CEJ. In these results, we came to conclusion that tensile stress generated from the centric occlusion may be related to the formation of NCCLs in a significant level. Not only eccentric occlusion but also centric occlusion seems to be related with the formation mechanism of NCCLs clinically observed in the buccal CEJ, the Level C, and they seems to generate stress concentration working together.

Grippo⁴¹ said that the high incidence of cervical abfraction lesions in Koreans is noteworthy and warrants investigation in his suggestions for future studies. But it is hard to find the epidemiologic study reported a strong association with a NCCLs and occlusal tooth wear except for one Korean study⁴². It is necessary to have further clinical study for NCCLs of Koreans together with epidemiologic study and this study of 3D FEA using the maxillary second premolar of a Korean might be the preliminary research.

V. CONCLUSIONS

1. The peak stress was seen at the cervical enamel surface of the mesiobuccal line angle area, asymmetrically.
2. The values of compressive stresses were within the range of the failure stress of enamel. But the values of tensile stresses exceeded the range of the failure stress of enamel.
3. The tensile stresses from the perpendicular load at buccal incline of palatal cusp may be shown to be the primary etiological factors of the NCCLs.

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국문초록

교합하중이 치경부 응력분포에 미치는 영향에 관한 3차원 유한요소법적 연구

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본 연구의 목적은 3차원유한요소분석법을 이용하여 정상 상악 제2소구치의 협측부의 응력분포에 다양한 교합응력이 미치는 영향을 평가하고자 하였다.

상악 제2소구치의 3차원유한요소모델을 형성한 후 형성된 모델에 3종류의 정적인 500N 점하중의 응력조건을 부여하였다. ANSYS 프로그램 (Swanson Analysis Systems, Inc., Houston, USA)으로 최대주응력과 최소주응력을 4개의 수평면 상(CEJ 상방 1 mm, CEJ 상방 0.5 mm, CEJ, CEJ 하방 0.5 mm)에서 분석하여 다음 결과를 얻었다.

1. peak stress가 협측 백악법랑경계를 따라 비대칭적인 모습으로 나타났다.
2. 압축응력 값은 법랑질의 압축파괴응력 범위 내에 있었지만 인장응력은 법랑질의 인장파괴응력 범위를 넘어섰다.
3. 비우식성치경부병소를 발생시키는 주요인은 설측교두의 협측경사면에 가해지는 교합압에 의한 인장응력이라고 보여진다.

주요어: 교합응력, 응력분포, 유한요소분석, 상악제2소구치, 압축응력, 인장응력