THREE-DIMENSIONAL FINITE ELEMENT STRESS ANALYSIS OF PORCELAIN INLAY AND ONLAY

Hyuk-Choon Kwon, Chung-Moon Um, Ho-Hyun Son, Byeong-Hoon Cho

Dept. of Conservative Dentistry, College of Dentistry, Seoul National University

ABSTRACT

도재인레이 및 온레이에 대한 삼차원유한요소법적 응력분석

서울대학교 치과대학 치과보존학교실

권혁춘 · 엄정문 · 손호현 · 조병훈

심미도재수복시의 와동의 폭과 교두의 capping이 응력의 분포에 미치는 영향을 비교하기 위하여 연속사진 촬영술을 이용하여 상악제1소구치의 3차원 유한요소 모델을 제작하였다. 법랑질, 상아질, 도재 및 복합레진시멘트의 각각의 재질에 대한 물성치를 부여하고, 140N의 하중을 가하여 Super SAP 프로그램으로 해석하여 다음과 같은 결과를 얻었다.

1. 응력은 탄성계수값이 큰 법랑질과 도재를 따라 분포되고, 연질의 상아질에는 적게 발생된다.
2. 와동의 협측치수선각부위에서는 인레이모델의 경우에는 와동폭의 증가에 따른 응력의 증가는 관찰되지 않으나, 온레이모델에서는 응력의 증가가 관찰된다.
3. 온레이모델의 경우에는 근심협측교두를 피개하고 있는 도재부위에 최대주응력이 크게 나타나고, 치은변연부의 도재에서는 교두를 피개하지 않은 인레이모델의 해당되는 법랑질에 비해 응력이 1/2정도로 감소된다.
4. 하중이 증가되면 잔존치질의 파절은 근심와동의 협측치은선각부위에서 협측보다는 치은을 향해 경사지게 일어날 것이다.
5. 교두를 피개하면 교두피개부위에서의 도재의 파절가능성은 증가되고, 치은변연에서는 도재와 하부의 치질의 파절가능성은 감소된다.
6. 도재를 이용하여 교두를 피개할 경우에는 응력을 견딜 수 있는 도재의 두께를 부여할 수 있도록 교두를 충분히 삭제하여야 하고, 충분한 강도를 갖는 도재를 선택하여야 한다.

Key words : porcelain onlay, three-dimensional finite element method, stress, isthmus width

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I. Introduction

Gold inlay or onlay preparations must have retention forms, for which a practitioner can use a combination of intracoronal and extracoronal tooth preparations, such as boxes, grooves, sharp internal line angles, shoulders and bevels. But, porcelain inlay or onlay preparations could be modified from those for a traditional gold inlay or onlay due to unique bonding characteristics. That is, they require uniform reduction of the tooth structure by 2.0 mm, round internal line angles, shoulders and butt-joint margins[1]. Among the several methods to produce porcelain inlays or onlays, the Cerec system and Celay system were recently introduced into the dental profession. Both systems use a milling machine to fabricate a porcelain prosthesis out of feldspathic and/or machinable glass-ceramic blocks.

Although the Cerec operator's manual recommends preserving as much healthy tooth substrate as possible, it does not clearly define the border between inlay and onlay. Rather, it says that the size of the cavity is irrelevant[2]. According to the Celay operating instruction, an onlay is indicated when the preparation borders extend over the top of the cusp[3]. But Sturdevant, et al. maintain that when the facial and/or lingual extension exceeds two-thirds of the distance from a primary groove toward the cusp tip, reduction of the cusp(s) for capping is mandatory for the development of adequate resistance form for amalgam and cast gold restorations[4]. Although it is widely accepted that resin luting cement strengthens the remaining tooth materials of a restored tooth with porcelain inlay, the durability of the bond has not been confirmed by clinical studies until now[5]. Therefore, Heymann, et al. recommend that clinicians must stick to the rule of cusp capping during cavity preparation for esthetic adhesive restorations; that is, a cusp should be capped if the extension is two thirds or greater from any primary groove to the cusp tip[4].

In order to compare the stress distribution in the restored teeth with size variables, especially isthmus width, and investigate the effect of cusp capping on the stress distribution, the finite element method (FEM) was utilized.

II. Materials and Methods

In order to investigate the stress distribution in the tooth restored with porcelain inlay or onlay, a three-dimensional finite element model of a mandibular first molar was developed. To construct the three-dimensional finite element models based on geometrical data from an actual tooth, the serial photographic technique was used[6,7]. A brief description of the development of the three-dimensional finite element model of class II MO inlay cavity preparation follows.

A mandibular first molar with no carious lesions, restorations, fracture of cusps, or wear, and with normal anatomical features, was selected. Ideal class II MO inlay cavity preparation was made in which the isthmus width was one-third of the intercuspal width, the depth of pulpal floor was 0.5 mm below the dentinoenamel juction (DEJ) and there was a butt-joint cavosurface margin. For an easy demarcation of the interface between tooth substrate and filling material in serial photographs, the cavity was filled with amalgam. The specimen was embedded in a self-curing acrylic resin block in an orientation in which the bucco-lingual axis of the specimen and the x-axis of the block were coincident with each other. For an accurate superimposition of serial photographs projected with a slide prejector at a pre-selected orientation and magnification, three parallel linear indentations along the z-axis of the block were given on the surfaces of the block coincident with the buccal and occlusal surfaces of the tooth.

The surface showing the mesial view of the specimen was sequentially ground by an automatic grinding machine (Struers Pedamat 4790430, Struers, Copenhagen, Denmark) and SiC paper grit 500 (Varus 40400070, Struers, Copenhagen, Denmark) to obtain the data about the geometric dimensions of the tooth. Horizontal reduction parallel to the plane of the mesial surface by approximately 0.5 mm was performed so that the z-coordinate could be given along the axis from the mesial to the distal surface of the tooth. The ground surface exhibited outlines of tooth structures and cavity preparations. The tooth surface was then photographed to record the geometries of the enamel, the dentin, the prepared cavity, the pulp chamber and the root canals. This grinding and photographing procedure was repeated until the distal surface of the tooth was completely ground off.

From a projected image of a ground section of the specimen on the screen, the indentations for monitoring the orientation and the magnification were traced onto a tracing paper, and the tracing was used as a reference. Another projected image of the next section of the specimen was superimposed on the reference tracing in a manner that all the indentations were accurately put on those of the reference tracing. Then, the boundaries of the enamel, the dentin, the pulp, and the filling body were traced onto a new tracing paper. After all the tracings were obtained, minor corrections were performed with average anatomical tooth form and cavity size and shape as reference. Simultaneously, different inlay or onlay cavities with varying isthmus widths were drawn on each tracing so that all the experimental cavity forms were included in a single FE model.

With the information obtained from tracings of eighteen serially ground sections at 0.5 mm intervals, a three-dimensional finite element model of the restored tooth was constructed. For analysis, in each section, the tracings were divided into rectangles of appropriate sizes. Then, eight-nodal linear isoparametric brick elements were formed by connecting corresponding nodes of the adjacent section sequentially. In this manner, a three-dimensional finite element model made of 4688 nodes and 3790 elements was constructed. Isotropic material properties of the enamel, the dentin, the porcelain and the luting resin cement assigned to this model were described in table 1.

Table 1. Material properties assigned to dental tissues and restorative materials in this study.

Materials	Modulus of Elasticity (Mpa)	Poissons ratio (ν)
Enamel	8.41×104*	0.30*
Dentin	1.83×104*	0.31†
Porcelain	7.00×104‡	0.28‡
Luting resin cement	2.00×104§	0.24§

* : Craig RG:Restorative Dental Materials, 8th ed. 1989[8].
† : Morin, et al.:Dent Mater 4:77-84, 1988[9].
‡ : Derand T:Dent Mater 7:21-24, 1991[10].
§ : Versluis A, et al.:J Dent Res 76(6):1298-1307, 1997[11].

In this study, five designs of restoration using porcelain inlay or onlay were used as models with the isthmus width and the cusp capping as variables. Cavity preparation designs were labeled as follows :

I-1 : Class II MO inlay restoration in which the isthmus width was one-third of the intercuspal width.

I-2 : Class II MO inlay restoration in which the isthmus width was two-thirds of the intercuspal width.

I-3 : Class II MO inlay restoration in which the isthmus width was equal to the intercuspal width.

O-1 : Onlay restoration with the mesio-buccal cusp capping in which the pulpal floor was flat from the central groove to the buccal wall.

O-2 : Onlay restoration with the mesio-buccal cusp capping in which the pulpal floor had an occlusal step of 0.5 mm on the mesio-buccal pulp horn area.

In each model, material properties of each element were defined as one of four material groups according to the location of each element in the restoration; that is, the enamel, the dentin, the porcelain and the luting resin cement. Boundary conditions were imposed in such a manner that the nodes in contact with the periodontal ligament were fixed in all directions to prevent bodily displacement of the root. Anderson and Picton reported chewing forces of the normal dentition to range from 18 to 31 pounds (8 to 14 kg) using a single molar tooth transducer[12]. In the present study, to evaluate stress distribution in a restored tooth, a force of 140 Newton was loaded vertically on the node that is present in the center of the inner incline of the median section of the mesio-buccal cusp. The Super

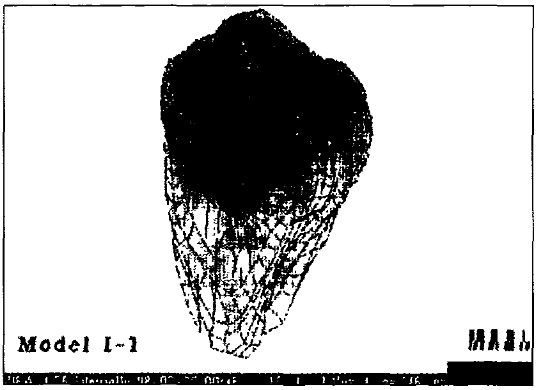

Fig 1. Three-dimensional FE model of the Class II MO porcelain inlay restoration in which the isthmus width was one-third of the intercuspal width.

Sap finite element method package (Algor Interactive System, Inc., Pittsburgh, PA) was used for calculations.

III. Results

In this study, a three-dimensional finite element model of the tooth with 5 different cavity preparations was obtained (Fig. 1).

To analyze typical stress distribution patterns within an inlay- or onlay-restored tooth, stress values along a series of selected nodes from the seventh section in a bucco-lingual direction, the mesio-distal section across the pulpal floor next to the buccal internal line angle of the cavity, and the horizontal section along the cervical margin were obtained. In the seventh bucco-lingual section, the maximal principal stress values within the porcelain along the cavity floor were much higher than those within the tooth substrate. In tooth substrate, there were no significant differences in stress values at the bucco-pulpal external line angle and the cervical enamel margin. Although the compressive and maximal principal stress values within the porcelain of the onlay models were much higher than those of the inlay models at the bucco-pulpal external line angle, the stress values of the onlay models were half of those of the inlay models at the cervical enamel margin (Fig. 2, 3). In Figure 2, nodes 1485 of I-1, 1485 and 1597 of I-2, and 1485,

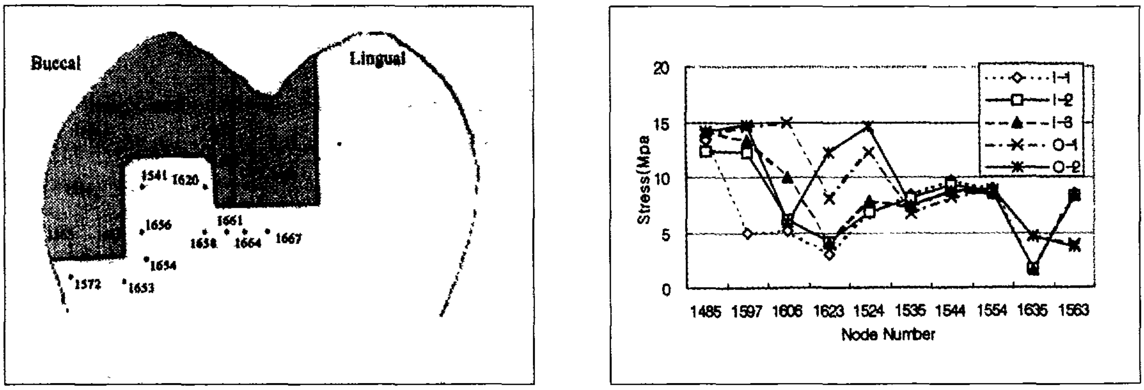

Fig. 2. Max Principal Stress Values within the porcelain at the pulpal floor of the seventh section

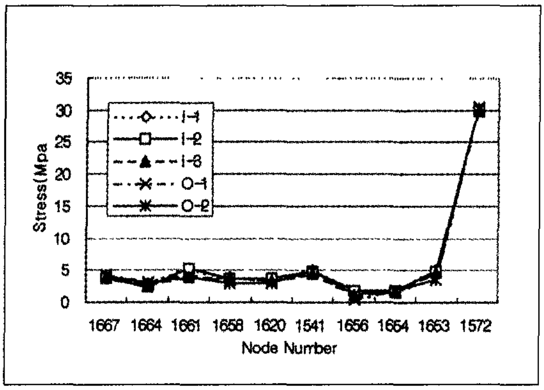

Fig 3. Max Principal Stress Values within the tooth at the pulpal floor of the seventh section

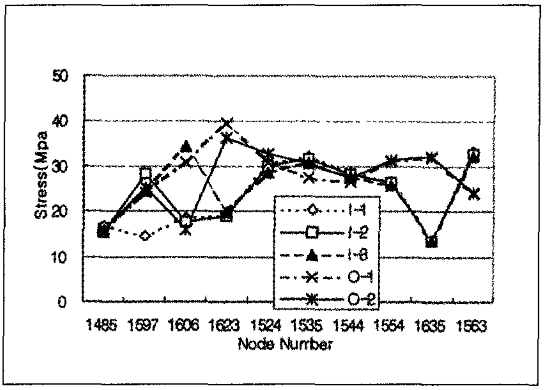

Fig 4. Von Mises Stress Values within the porcelain at the pulpal floor of the seventh section

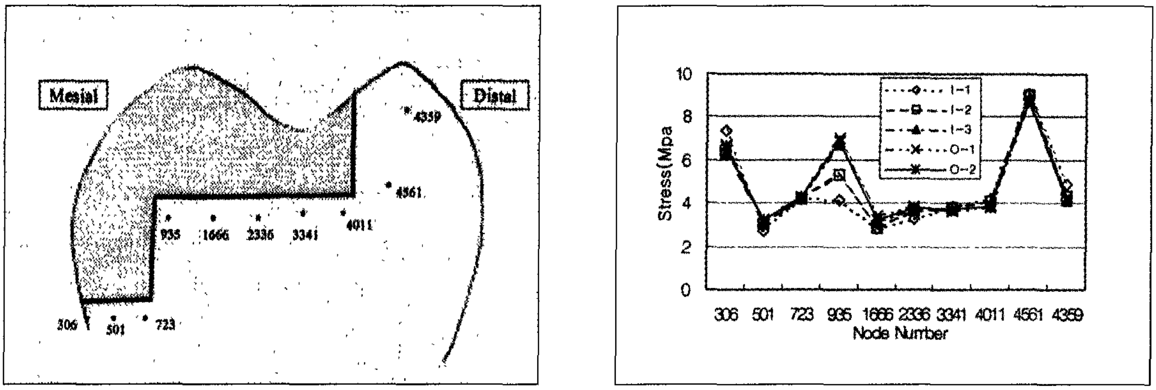

Fig 5. Max Principle Stress Values within the tooth at the pulpal floor of the mesio-distal section.

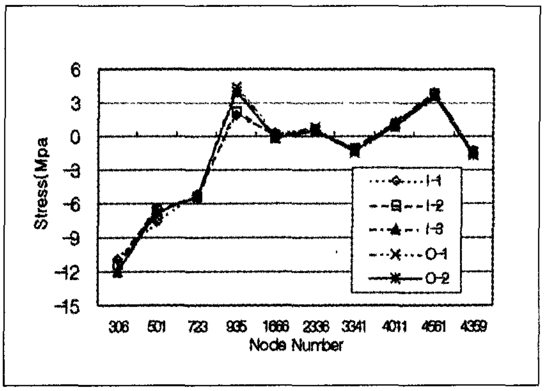

Fig 6. Stress Values in the bucco-lingual direction within the tooth at the pulpal floor of the mesio-distal section

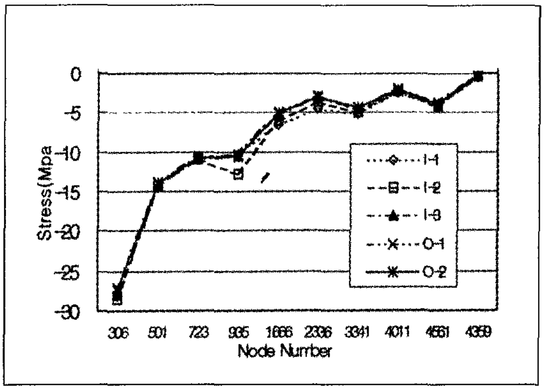

Fig 7. Stress Values in the vertical direction within the tooth at the pulpal floor of the mesio-distal section

1597, and 1606 of I-3 were within the porcelain, but the other nodes of these models were within the tooth substrate. Node 1623 of each model was present within the dentin and showed lower stress values than corresponding nodes of the onlay models. The nodes along the dentino-enamel junction of the

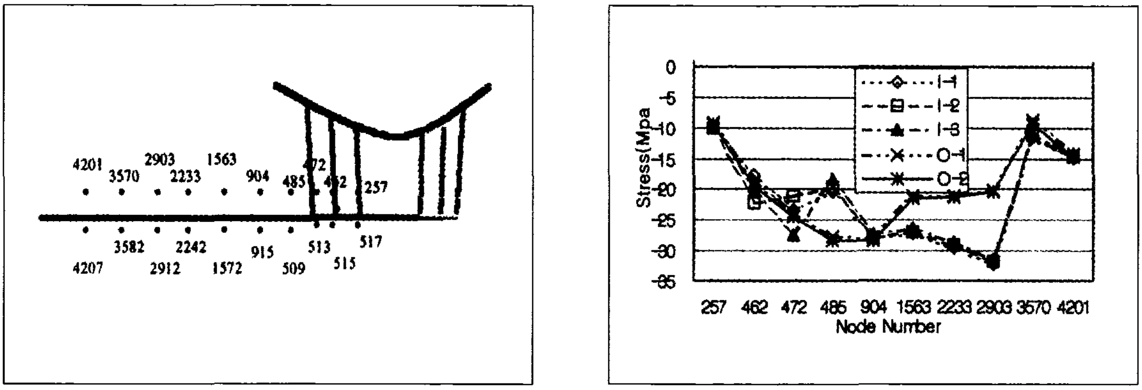

Fig 8. Stress Values in the vertical direction within the porcelain at the cervical margin.

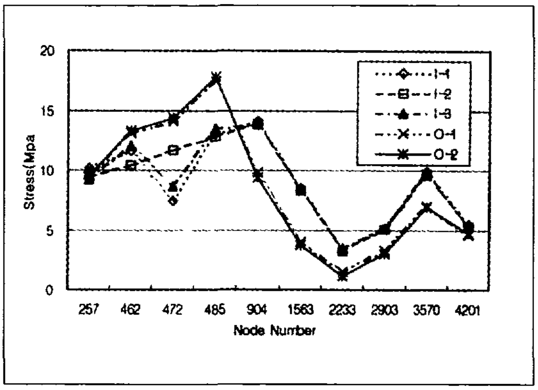

Fig 9. Max Principle Stress Values within the porcelain at the cervical margin

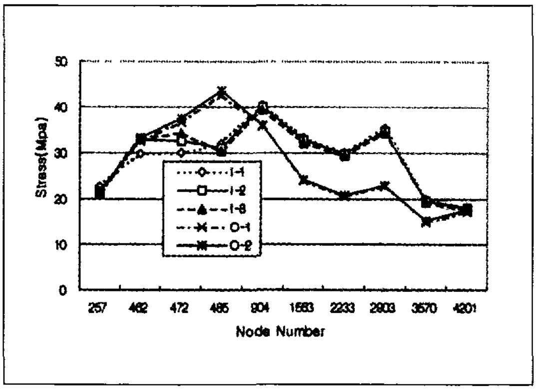

Fig 10. Von Mises Stress Values within the porcelain at the cervical margin

inlay models(from #1524 to #1554) showed similar stress values with corresponding nodes of the onlay models. But the highest stress values were observed within the enamel(#1572) under the cervical margin and/or near the cemento-enamel junction in all the models. Von Mises stress values within the porcelain of the onlay models were much higher than those within the dentin of the inlay models both beyond the occlusal step(#1623) and at the cervical shoulder area(#1635) (Fig. 4).

Maximal principal stress values within the tooth at the pulpal floor were very low, but at the axio-pulpal line angle(#935), stress increased along with the increase of the isthmus width (Fig. 5). At the gingival wall of the mesial proximal box(#306, 501, 723), compressive stress values in vertical direction were twice as high as those in the bucco-lingual direction (Fig. 6, 7).

From the stress values along the cervical margin, at the mesio-buccal line angle(#485), maximal principal stress, Von Mises stress and compressive stress values in the bucco-lingual and vertical directions of the onlay models were much higher than those of the inlay models because corresponding nodes of the inlay models were made of tooth substrate. At the cervical margin of the buccal shoulder covering the mesio-buccal cusp(#1563, 2233, 2903), although compressive stress values in the vertical direction within the porcelain of the onlay model were higher than those within the enamel of the inlay models, Von Mises stress and maximal principal stress values within the porcelain of the onlay models were lower than those in the enamel of the inlay models (Fig. 8, 9, 10). But, within the

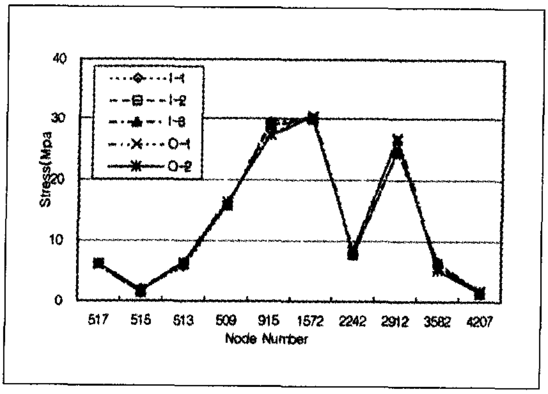

Fig 11. Max Principle Stress Values within the tooth at the cervical margin

enamel under the cervical margin, all types of stresses showed similar distribution pattern. That is, at the buccal area under the cervical margin of the mesio-buccal cusp(#915, 1572), very high maximal principal stress, Von Mises stress and compressive stress values in the vertical direction were observed in all the models (Fig 11).

IV. Discussion

Most dental hard tissues and materials are brittle by the nature; that is, such material groups as the enamel, the dentin, the porcelain, and the composite resin, have high compressive strength and relatively low tensile strength. For the evaluation of the behavior of these materials under load, tensile stress values in each direction are more valuable than compressive ones, and the principal stress values at a certain point are useful for overall evaluation[7, 13]. Because the aim of this experiment was to evaluate the stress distribution within the restored tooth with porcelain inlay or onlay and to investigate the effect of the cusp capping on the stress distribution, the distributions of the maximal principal stress values were compared first and with the data as reference those of the tensor stress values in the bucco-lingual and the vertical direction were compared.

The porcelain and the enamel are highly inorganic materials in their composition and have much higher values in Young's Elastic Modulus than the dentin which has abundant organic components. Therefore, if a load is given onto a tooth, high maximal principal stress values would be induced within the enamel and the porcelain and the stress would be transmitted along the harder porcelain and enamel rather than to the softer dentin in spite of the presence of softer luting resin cement between the porcelain and the enamel.

There was no increase in various stress values at the the bucco-pulpal line angle as the isthmus width in the inlay models increased. But there were distinct differences between the inlay and the onlay models. In the onlay models, occlusal load exerted onto the porcelain produced high maximal principal stress values within the porcelain capping the mesio-buccal cusp, but at the cervical margin these stress values within the porcelain were half of those at the corresponding nodes within the enamel. Those within the remaining dentin were very low in quantity and showed similar distribution patterns among all the models. The highest maximal principal stress values were observed within the enamel under the bucco-cervical margin and their values were similar among all the models because the elastic modulus value of the enamel is higher than that of the porcelain.

In both the inlay and onlay models, at the gingival wall of the mesial proximal box, the compressive stress values in the vertical direction were twice as high as those in the bucco-lingual direction. Therefore, if excessive force was applied, fracture of the remaining tooth substrate would happen more gingivally than buccally from the bucco-gingival line angle of the proximal box.

Because a large proportion of the stress was absorbed by the rigid porcelain and the stress values within the porcelain of the onlay models were higher than those within the enamel of the inlay models at the area which corresponds to the cusp-capping areas, the fracture potential of the porcelain at the capping areas will increase by capping the cusp. But because stress values within the porcelain and the underlying enamel around cervical margin decreased in comparision with those within the cervical enamel of the inlay models, the fracture potential of the porcelain and underlying tooth substrate at the cervical margin areas will decrease by capping the cusp. Therefore, when capping a cusp, a practitioner must reduce the cusp by a thickness which is enough for the porcelain to withstand the stresses and select a material which has an appropriate strength, as well.

V. Conclusions

In order to investigate the stress distribution in the tooth restored with porcelain inlay or onlay, a three-dimensional finite element model of a mandibular first molar which had five different designs was developed, and the stress distributions were evaluated. The results were as follows :

1. Stress was transmitted along the harder porcelain and enamel rather than to the softer dentin
2. There was no increase in various stress values at the bucco-pulpal line angle with the increase of isthmus width in the inlay models. But there were distinct differences between the inlay and the onlay models.
3 High maximal principal stress values were observed within the porcelain capping the mesiobuccal cusp, but at the cervical margin, these stress values within the porcelain were half of those at the corresponding nodes within the enamel of the inlay models.
4. If excessive force was applied, fracture of the remaining tooth substrate would happen more gingivally than buccally from the bucco-gingival line angle of the proximal box.
5. The fracture potential of the porcelain at the capping areas will increase, but those of the porcelain and underlying tooth substrate at the cervical margin areas will decrease by capping the cusp.
6. When capping a cusp with porcelain, a practitioner must reduce the cusp by a thickness which is enough for the material to withstand the stresses and select a material which has an appropriate strength.

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