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Effects of cantilever design and material on stress distribution in fixed partial dentures – a finite element analysis

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SUMMARY The purpose of this study was to examine the stress distribution in distal cantilevered fixed partial dentures (FPDs) that are designed with different cantilever morphology and made from different restorative materials. The finite element (FE) method was used to create models of two restoration types; metal-ceramic and an all-ceramic FPDs. Both models were designed with distal cantilevers involving the first and second premolars as abutments and cantilever extension involving at the premolar or molar. The width of connector between the cantilever and the primary abutment restoration was 2·25 mm. The load applied during the FE analysis was positioned at the cusp tips of all teeth. The FE analysis of the models revealed that Von Mises stress values with maximum stress concentrations were observed on connectors of distal cantilevers. Stress concentration sites were also observed at the distal cervical area of the second premolar tooth. Models with premolar cantilever extensions restored with all-ceramic induced lower Von Mises stress values than metal-ceramic restorations, however models with molar cantilever extensions restored with all-ceramic restorations induced higher Von Misses stress values than metal-ceramic restorations. If the distal cantilever length and restorative material is appropriately chosen, the failure frequency may be reduced. All ceramic can be used as restorative material, when the cantilevers length is not more than the mesiodistal dimension of a premolar tooth and metal-ceramic restorations can be used in longer situations.

KEYWORDS: finite element analysis, distal cantilever, fixed partial denture, all-ceramic, metal ceramic

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Introduction

Several different prosthetic designs can be used to restore missing teeth. In some situations, it is not possible to use two abutment teeth at each end of the edentulous area to support the fixed partial dentures (FPDs). In such a clinical situation, a FPD can be designed with a distal cantilever to replace missing teeth (1, 2). A cantilever is defined as a FPD which has an abutment or abutments at one end with the other end of the pontic remaining unattached (1). This can potentially be a biomechanically destructive design to the tooth structures when it is misused (1). In such situations the FPD design, and the material used in fabrication of the restoration are very important for mechanical reasons and survival of the restoration (3, 4).

The stresses in a cantilevered FPD can be assessed by finite element (FE) analysis method. The effect of stress on a cantilever, consisting of a ductile alloy in contact with a brittle material such as porcelain, was demonstrated to be complex (5, 6). The distribution of stress also influences the treatment success. Possible fracture and distortion of both alloy and ceramic materials have been previously demonstrated (5–7).

Periodontal response to cantilevered restorations, differences of loads placed on periodontal ligament, relation between the thickness and length of pontics and bending-deflection of dentures have been investigated by several authors (8–11). Clinical and radiographic evaluations of these type of restorations have also been performed (12–14). Many stress analyses methods are being used recently. But recent developments at computer technology have advanced the FE stress analyses method with features of ability to get close to reality in matter of design and analyses (15, 16). The FE method has been used as a methodology for investigation of cantilevered prostheses by several authors (15, 17–21). This method have been introduced in dentistry and used in FPDs, implantology, orthodontics, partial prostheses and restorative dentistry (22).

Abutment and pontics are united by a connector that satisfies certain structural requirements. It must provide enough strength to resist the forces of occlusion that cause flexure of the connector, the interface, and the abutment casting (2, 23). Therefore, to develop theories of FPD design, the amount of stress likely to be generated in the oral cavity must be quantified. Masticatory loads are difficult to measure, but maximal biting force is a useful baseline parameter. It has been reported that the maximal biting force in the first molar region between 300 and 500 N (5).

The hypothesis tested in current study was that the stress values at premolar cantilevered FPDs are lower than the molar cantilevered FPDs. Recognizing the uncertainty of the effects of the morphology of the cantilever, and the effects of the restorative materials on stress distribution in a FPD, this study was initiated to investigate the criteria for successful treatment planning of a cantilevered FPD.

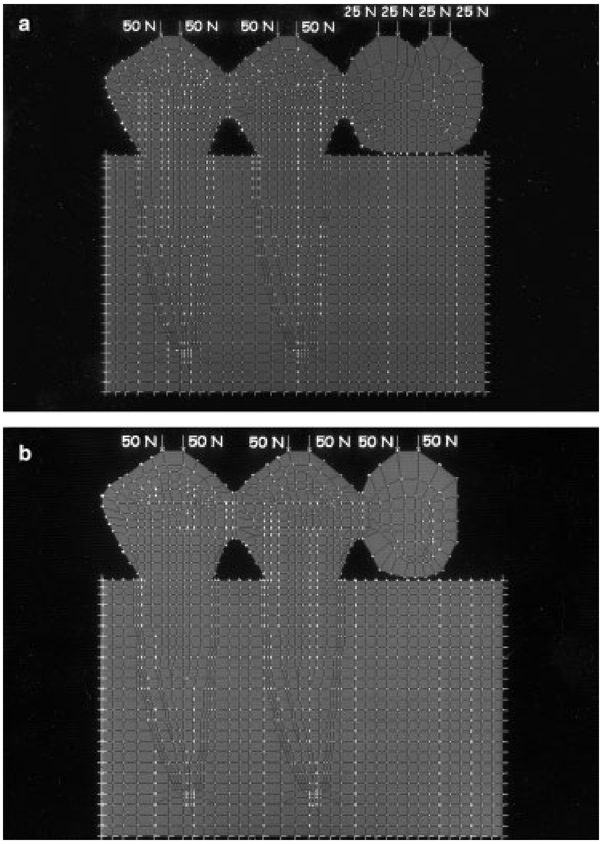

Fig. 1. Pseudo three-dimensional finite element model (a) loading conditions and constrained nodes of restoration with premolar cantilever. (b) Loading conditions and constrained nodes of restoration with molar cantilever.

Materials and methods

Four different FE models simulating the first and second premolar teeth restored with either a metal-ceramic or all-ceramic restoration (IPS Empress 2 system)[*] with distal cantilevers having two different teeth morphology (premolar or molar) and supporting bone (Fig. 1a, b).

The effect of the material was investigated by changing the restoration materials (metal-ceramic restoration made of Ni-Cr alloy and feldspatic porcelain, and IPS Empress 2 core, lithium-disilicate, and its own veneering porcelain restoration). The FE program used was a two-dimensional plane stress analysis with provision for inputting material thickness values in the third dimension. Models were drawn with the Sap2000 structural analysis program Nonlinear Version 7·12[†]. The geometry of the teeth has been described by Wheeler (24). Length of the roots were modelled as 14 mm and the crown/root ratio were approximately 1/2. The applied forces were static. The standard model composed of 1751 nodes, 88 restrains and 1700 elements. Abutments have been modelled according to a standard 3-unit FPD design utilizing complete crown preparations. Although manufacturer's instruction for core thickness of IPS Empress 2 is 0·8 mm; a core thickness of 0·5 mm was used in this study to make the core comparable with the metal framework of the metal-ceramic test group. Shoulder margin type has been selected for preparations. Rigid connectors of a FPD were designed with a 2·25 mm thickness occluso-cervically and curved connector geometry has been used. The average width of the periodontal ligament and cortical bone were 0·25 mm. Cement thickness was ignored.

Load was applied at the cusp tips of all three teeth; 100 N per each cusp tips of premolar abutments. For

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[*] Ivoclar, Schaan, Liechtenstein.

[†] Computer and Structures Inc., Berkley, CA, USA.

Table 1. Mechanical properties of materials

Material	Elastic modulus (*E*) (GPa)	Poisson's ratio ()	Reference no.
Feldspatic porcelain	82·8	0·35	25
Metal alloy (Ni-Cr)	206	0·33	26
IPS Empress 2 (veneer material)	60	0·23	27
IPS Empress 2 (core material)	96	0·25	27
Dentine	18	0·33	22
Pulp tissue	·003	0·45	28
Periodontal ligament	·069	0·45	29
Cortical bone	13·7	0·3	30
Spongy bone	1·37	0·3	30

models with premolar cantilever extensions, two points vertical load applied at buccal cusp (50 N each) (Fig. 1a) and for models with molar cantilever extensions, four points vertical load applied at two buccal cusps (25 N each) (Fig. 1b).

Lower, mesial and distal borders of the supporting bone were considered fixed in all directions for resistance of the FE model to the occlusal loads. Mechanical properties of the materials were taken from previous literature (Table 1) (22, 25–30).

All materials were presumed linear elastic, homogenous and isotropic (31). Elastic modulus and Poisson's ratio of the materials, along with the coordinate and geometry of each node and element, were entered to a computer. Sap2000 structural analysis program was used to solve the stress analysis problems.

Calculated numeric data were transformed into colour graphics to better visualize mechanical phenomena in the models. Stress levels were calculated using Von Mises stress (32–34) values. Von Mises stress values are defined as the beginning of deformation for ductile materials such as metallic restorative materials (33).

Results

The analysis of the Von Mises stress values for all models revealed that a higher stress located at occlusal embrasure of the connector between pontic and second premolar abutment compared to the cervical embrasure. Occlusal and gingival embrasures of connectors were the areas of more intensive stress concentrations. Other stress concentration sites were distal cervical area of the second premolar tooth, the connector between first and second premolar, and apical part of each premolar's root, respectively in amount. Stress concentration at the apical part of second premolar root was greater than that of first premolars' (Fig. 2).

When metal-ceramic versus all-ceramic (premolar) models compared, Von Misses stress values at all-ceramic restorations were lower (1·08 N mm^{-2}) than metal-ceramic restorations (1·17 N mm^{-2}).

In metal-ceramic versus all-ceramic (molar) comparison, Von Misses stress values at all-ceramic restorations were higher (1·71 N mm^{-2}) than metal-ceramic restorations (1·62 N mm^{-2}). Investigation of connectors has

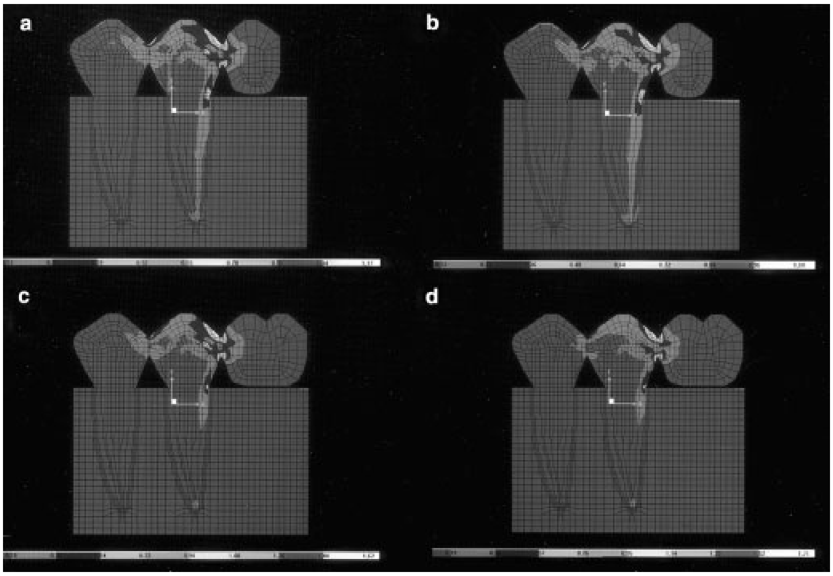

Fig. 2. Von Mises stresses in finite element models with 2·25 mm connector width [a, c: Metal-ceramic; b, d: All-ceramic (IPS Empress)].

shown that the higher stress concentrations observed at the porcelain part of connectors of metal-ceramic restorations (Fig. 2).

Discussion

The results of current study have supported the hypothesis investigated. Stress values at premolar cantilevered FPDs were lower than the molar cantilevered FPDs.

There are no explicit guidelines in the literature for interpreting the results of neither stress analysis, nor are there any suggestions regarding the kind of stresses that must be used in the explanations. Principal stresses and Von Mises stress have been used equally (33). Von Mises stresses are most commonly reported in FE analysis studies to summarize the overall stress state at a point. Von Mises stress values are defined as the beginning of deformation for ductile materials such as metallic restorative materials. As failure occurs when Von Mises stress values exceed the yield strength of a metallic material, Von Mises stress criteria are important for interpreting the stresses occurring within the metallic FPD material (33). Thus, Von Mises stress criterion has been used in this study.

The model used in this study implied several assumptions regarding the simulated structures. The structures in the model were all assumed to be homogeneous, isotropic and to possess linear elasticity. The properties of the materials modelled in this study, particularly the living tissues, however, are different. Also, it is important to point out that the stress distribution patterns may have been different depending on the materials and properties assigned to each layer of the model and the model used in the experiments. Thus, the inherent limitations in this study should be considered.

Connector size is an important factor on durability of restoration. The connector must be thick enough to provide adequate resistance to occlusal loads, however, occlusal and gingival embrasures must be formed such as to ensure aesthetics of restoration (1, 2). Thus, in the current study the model have been developed as having a connector height of 2·25 mm which is approximately one-third of crown length.

When applying FE analysis to distal cantilevers, it is important to consider not only axial loads and horizontal forces (moment-causing loads) but also a combined load (oblique occlusal force) because the latter represents more realistic occlusal directions and, for a given force, will result in localized stress in cortical bone (16). In the current study, only vertical loads were considered.

The *in vivo* greatness of occlusal force is selected standard 100 N value. However, it is not necessary for this force to match the reality exactly because of the standardization between conditions has been ensured in current study and the conditions have been compared qualitatively with each other. Chen and Xu (35) have emphasized that the value of FE modelling is in relative values calculated at distribution pattern.

The design of the occlusal surface of the model can influence the stress distribution pattern. In the current study, the locations for the force applications were specifically described as cusp tips. However the geometric shape of the tooth surface can produce a pattern of stress distribution that is specific for the modelled shape. The pattern could be different with even moderate changes of the occlusal surface of the crown. This occlusal shape used for this model does not mean that the same shape would represent all premolar teeth and molar teeth.

In addition to the increased load placed on the periodontal ligament by a long span FPD, longer spans are less rigid. Bending or deflection varies directly with the cube of the occlusogingival thickness of the pontic (1, 9). If everything else remains unchanged, a FPD with a two tooth pontic span will bend eight times as much as a single tooth pontic FPD will. In addition, making the pontic one half as thick will also make it bend eight times as much. When the pontic is loaded occlusally, the adjacent abutment tends to act as a fulcrum, with a lifting tendency on the farthest retainer (1, 10, 11). To minimize the leverage effect, the pontic should be kept as small as possible, more nearly representing a premolar than a molar (1, 23). Nevertheless, the pontic should possess maximum occlusogingival height to ensure a rigid FPD (1). The results of current study are parallel to those knowledge that as the length of distal cantilever increases, the amount of the stresses occurs in restorations increase.

It is important to take all the applicable parameters into account when planning and treating situations involving FPDs with distal cantilevers. If success is to be attained, the dentist must take into account the opposing occlusion, periodontal bone loss, attachment apparatus, length of span, crown-root ratio, and inclination of abutment teeth (2). In the light of current findings, material and FPD design should be added to risk factors which are effective in success of restoration and clinician must avoid using pontics longer than mesio-distal dimension of a premolar tooth as far as possible.

Conclusion

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

1. Simulating different types of distal cantilever morphology and the materials used for restoration affected stress distribution and stress values around the connectors and cervical region of distal support tooth.
2. Maximum Von Mises stress values were concentrated on connectors between distal cantilevers and second premolar.
3. Models with premolar cantilever extensions restored with IPS Empress restorations induced lower Von Mises stress values than metal-ceramic restorations.
4. Models with molar cantilever extensions restored with IPS Empress Von Misses stress values were higher than metal-ceramic restorations.

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