BASIC SCIENCE RESEARCH

Biomechanics of Cantilever Fixed Partial Dentures in Shortened Dental Arch Therapy

S.A. Romeed, DDS, MSD, PhD;[1] S.L. Fok, BEng, PhD, CEng;[2] and N.H.F. Wilson, MSc, PhD, DRD, FDS[3]

Purpose: The purpose of the present study was to investigate, by means of 3-dimensional finite element analysis, aspects of the biomechanics of cantilever fixed partial dentures replacing the maxillary canine in shortened dental arch therapy. The null hypothesis was that no differences would be identified by finite element analysis in the mechanical behavior of the 2 designs of cantilever fixed partial denture under different scenarios of occlusal loading.

Materials and Methods: Single- and double-abutted cantilever fixed partial dentures were modeled and analyzed using the finite element packages PATRAN® and ABAQUS®. Displacement and maximum principal stresses (magnitude and location) within the fixed partial dentures, supporting structures, and the periodontal ligament/bone and abutment/retainer interfaces were examined under 20 different scenarios of axial and lateral occlusal loading.

Results: The results indicate that more displacement occurred in the 2 rather than the 3-unit cantilever fixed partial denture, with the greatest displacement having occurred under lateral loading. The maximum principal stresses observed in the periodontal ligament/bone interfaces were greatest buccocervically, with the highest value being observed in the 2-unit fixed partial denture under lateral loading. The highest maximum principal stresses observed in the retainer/abutment interfaces were located cervically in relation to the distal margin of the retainer of the 2-unit fixed partial denture under axial loading.

Conclusions: It was concluded that in adopting a cantilever fixed partial denture approach for the replacement of a missing maxillary canine in shortened dental arch therapy, there may be merits, in terms of mechanical behavior, in selecting a double-rather than a single-abutment design. Furthermore, prostheses' displacement and functional stresses may be minimized by reducing lateral loading and avoiding pontic only loading.

J Prosthodont 2004;13:90-100.

INDEX WORDS: 3-dimensional finite element analysis, stress distribution

A SHORTENED DENTAL arch (SDA) as described by Kayser is an arch within a dentition in which most, if not all, of the molar teeth are missing.[1] The SDA has been extensively researched for more than 2 decades. This research has indicated that accepting rather than restoring an SDA is a suitable treatment option for patients with a reduced dentition, including compromised molars, and limited opportunity to secure the benefit of advanced restorative care to manage their progressive dental disease. A number of longitudinal clinical studies have concluded that SDA therapy meets the functional and cosmetic requirements of patients, providing them with oral comfort and confidence in eating and socializing.[2-5]

A relatively common problem in the provision of SDA therapy is the replacement of a missing maxillary canine, particularly in elderly patients (>45 years of age) of low socio-economic status.[6] As in the other forms of fixed prosthodontic

[1]Postgraduate student, Department of Restorative Dentistry, University Dental Hospital of Manchester, Higher Cambridge Street, Manchester M15 6FH, England, U.K.

[2]Lecturer in Mechanical Engineering, Manchester School of Engineering, Oxford Road, Manchester M13 9PL, England, U.K.

[3]Professor of Restorative Dentistry, Guy's, King's and St. Thomas' Dental Institute, King's College, London SE1 1UL; formerly, Professor of Restorative Dentistry, University Dental Hospital of Manchester, Higher Cambridge Street, Manchester M15 6FH, England, U.K.

Accepted August 4, 2003.

This paper was presented at the IADR meeting/San Diego, March 6–9, 2002.

Correspondence to: S.A. Romeed, Department of Restorative Dentistry, University Dental Hospital of Manchester, Higher Cambridge Street, Manchester M15 6FH, England, U.K. E-mail: romeed@hotmail.com

1059-941X/04

doi: 10.1111/j.1532-849X.2004.04004.x

treatment, a missing maxillary canine may be replaced in SDA therapy by means of a fixed partial denture (FPD) of a number of possible designs, or by means of implant therapy, the choice of approach being influenced by many interrelated factors unique to individual cases, including the patient's preferences, and the judgment, skills, and attitude of the clinician.[7] An understanding of the biomechanics of the alternative approaches is considered important in understanding the limitations of possible restorations, and in selecting the restorative option that best meets the patient's needs, with the best possible clinical outcome.

Considering the FPD options for the replacement of a missing maxillary canine, considerable debate has centered around the advantages and disadvantages of fixed–fixed (abutment–pontic–abutment) versus cantilever designs in situations in which either approach could be justified.[8] Regarding cantilevered FPDs, longitudinal studies over a period of <18 years have indicated a success rate of 70%, with many of the failures observed being attributed, at least in part, to an unfavorable distribution of forces within the prosthesis.[9] Other important factors in the success of cantilevered FPDs include the number and location of the abutments, the tooth being replaced and the type of the retainers to be employed; full-coverage retainers having many advantages over alternative retainers, notwithstanding the extent of tooth preparation necessary to successfully complete a full crown.[10]

A further key factor in the performance of cantilever FPDs is the number of abutments. The creation of a "super abutment" by splinting abutments together may limit the forces transmitted to the abutment adjacent to the pontic. However, "double abutting" in the provision of cantilever FPDs has a number of disadvantages, including the involvement of an additional tooth in the prostheses and possible periodontal complications.[11]

While distal design cantilever FPDs may have certain indications in the replacement of, for example, a missing second premolar in SDA therapy, the indications for FPDs of such design in the replacement of a maxillary canine are considered extremely limited.

The purpose of the present study was to investigate the mechanical behavior of 2- and 3-unit mesial cantilever FPDs replacing a maxillary canine by means of finite element analysis (FEA). The null hypothesis was that no differences would be identified in the biomechanics of the 2 FPD designs under different axial- and lateral-occlusal loading scenarios when investigated by FEA.

Materials and Methods

Modeling

Two 3-dimensional finite element models were created using PATRAN® (Patran2000r2, MSCsoftware, Santa Ana, CA). The first model was a 2-unit cantilever prosthesis extending from a maxillary first premolar (Fig 1A). The second model was a 3-unit cantilever FPD extending from a maxillary second premolar (Fig 1B). Details of the relevant tooth anatomy including naturally occurring differences in size and form were obtained from the existing literature.[12] The periodontal ligaments were modeled with a standardized thickness of 0.5 mm in both models. A 2-layered supporting bone structure was included in the models: cortical bone of 1.5-mm thickness and cancellous bone of 18.5-mm thickness, together forming a section of the maxilla (Figs 1A and B).

Full-coverage, porcelain fused to metal (PFM) retainers of traditional design,[13] perfectly fitted to a 1.5-mm deep shoulder, were modeled with the connectors between the retainers and pontics of a standardized design with a depth of 5.4 mm and a width of 1.75 mm. The interfaces between the retainers and their abutments were considered rigid. As a consequence, no cement lute was included in the models. Composition of the finite element model for the 3-unit cantilever FPD and supporting structures is shown in Figure 2.

Mesh Generation

The models of the FPDs and their supporting structures were meshed with 20-noded hexagonal elements. Boundary conditions were set for each model to simulate physiological conditions, that is, the degrees of freedom perpendicular to the boundaries surrounding the supporting bone structure, except in relation to the occlusal and buccal surfaces of the supporting bone, which were constrained (Fig 1).

Increasingly refined meshes were applied to the models to ensure that the predicted stresses converged to an accuracy of 90%. Details of the finite element meshes used for the models of the 2 FPDs and the supporting structures are given in Table 1.

Properties of the Materials

The mechanical properties given to the materials and tissues included in the models were taken from the existing literature,[14,15] and are summarized in

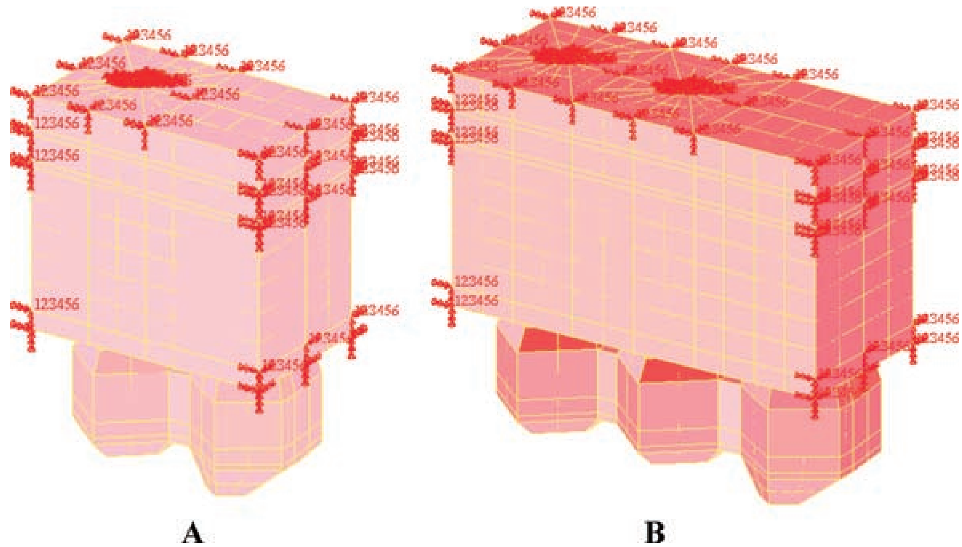

Figure 1. Finite element models of the 2-unit (A) and 3-unit (B) fixed partial dentures and the supporting tissues illustrating the finite element meshes and their boundary conditions.

Table 2. The materials and tissues were considered to be isotropic, homogenous, and linear elastic.

Loading

Loads of 50 N were applied either axially to the occlusal surface or laterally at an angle of 45° to the internal slopes of the buccal cusps of the retainers and pontics in a total of 20 loading scenarios. In the case of the 2-unit FPD, axial loads were applied to the retainer only, just to the pontic, and then to both the retainer and the pontic, simultaneously. This was repeated with lateral loads being applied to the internal slopes of the buccal cusps. In the 3-unit FPD, axial and then subsequently lateral loading was applied to the distal retainer, the mesial retainer, the pontic, 2 units at a time (×3), and finally all 3-units, giving a total of 14 loading scenarios to add to the 6 scenarios in the 2-unit FPD model.

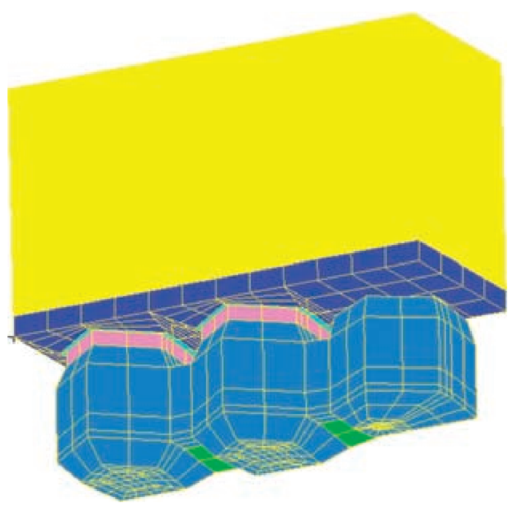

Figure 2. Components of the finite element model: yellow, cancellous bone; navy blue, cortical bone; sky blue, periodontal ligament; pink, dentin; green, gold alloy; light blue, ceramic.

Solution

For each of the 20 loading scenarios, the resultant displacements and stresses were calculated using ABAQUS® (Version 6.1-1, HKS, Pawtucket, RI). The displacement and stresses were then post-processed using PATRAN® to display the results in the form of displaced shapes and stress contour fringes. The locations and magnitudes of the maximum displacement and the greatest maximum principal stress were identified.

Results

Displacement

Axial loading of both the retainer and the pontic of the 2-unit FPD produced the greatest

Table 1. Details of the Finite Element Meshes

Model	*Number of Nodes*	*Number of Elements*
2-unit design	9778	2124
3-unit design	17122	3800

Table 2. The Mechanical Properties of the Materials and Tissues Included in Finite Element Models

Material	*Young's Modulus (MPa)*	*Poisson's Ratio*
Dentin[14]	18×10^3	0.31
Periodontal ligament[14]	6.9	0.45
Cortical bone[14]	1×10^4	0.30
Cancellous bone[14]	250	0.30
Casting gold[15]	90×10^3	0.3
Porcelain[15]	70×10^3	0.19

displacement (0.17 mm). Loading only the pontic in the 2-unit FPD resulted in a displacement of 0.15 mm as shown in Figure 3A. The corresponding values for the 3-unit FPD were 0.11 mm and 0.09 mm as shown in Figure 4A, with the greatest displacement of the 3-unit FPD (0.12 mm) occurring when the pontic and the adjacent retainer were simultaneously loaded. In the other scenarios of axial loading, FPD displacement ranged from 0.02 mm to 0.08 mm.

Under lateral loading, the displacement of the 2-unit FPD was greater than under axial loading, and greater than the displacement observed in the 3-unit FPD under both axial and lateral loading. When loading was applied laterally to the pontic only in the 2-unit FPD, the maximum displacement was 0.24 mm (Fig 3B). Simultaneous lateral loading of the 2-unit FPD retainer and pontic gave a displacement of 0.39 mm. The corresponding values in the 3-unit FPD were lower (0.13 mm), as illustrated in Figure 4B. Displacement did not exceed 0.2 mm in either FPD model under any of the abutment lateral loading scenarios investigated.

Stresses

The 2-unit FPD had the highest maximum principal stresses (15 MPa) under axial loading of the pontic and retainer simultaneously; these stresses were within the supporting cortical bone. Axial loading applied to the pontic only produced highest maximum principal stresses (13.8 MPa) within the distal cervical region of the abutment close to the retainer margin (Fig 5A). In the same model, all lateral loading scenarios generated considerably higher levels of maximum principal stresses in the lingual cervical region of the abutment close to the retainer margin (32.2 MPa) and in the supporting structures (16.9 MPa) (Fig 5B). In general, maximum principal stresses under axial loading of the abutment only were 50% of those observed with lateral loading.

The highest maximum principal stresses under axial loading (19.5 MPa) of the 3-unit FPD were recorded when all the units were loaded simultaneously, as in the model of the 2-unit FPD. Axially loading the 3-unit pontic only generated maximum principal stresses similar to those observed

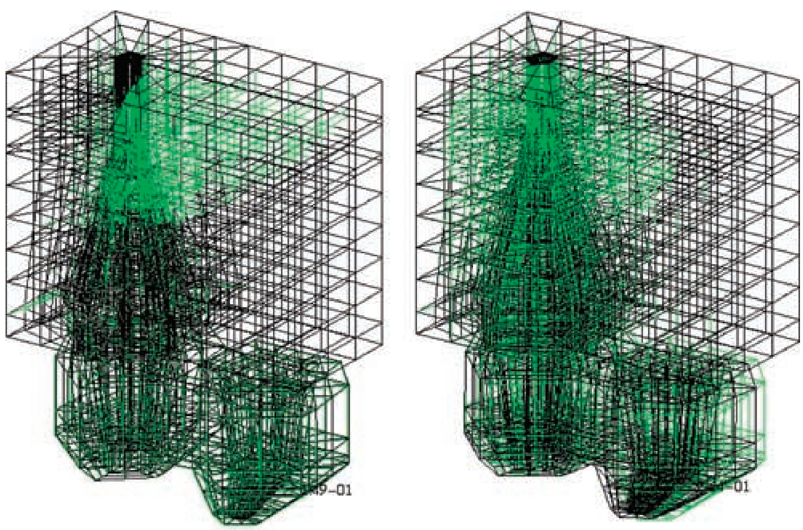

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Figure 3. Displacement in the 2-unit FPD: (*A*) 50 N applied axially to the pontic only; (*B*) 50 N applied laterally to the internal slope of the buccal cusp of the pontic only.

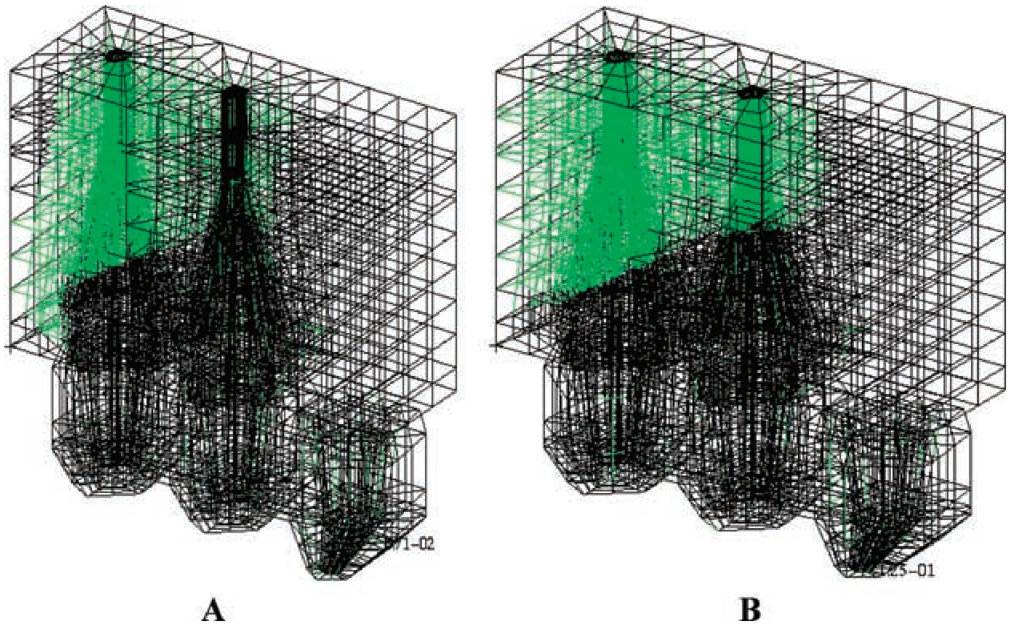


Figure 4. Displacement in the 3-unit FPD: (*A*) 50 N applied axially to the pontic only; (*B*) 50 N applied laterally to the internal slope of the buccal cusp of the pontic only.

in the 2-unit FPD under similar loading conditions. The distribution of these stresses differed, however, between the 2 models (Fig 6A). In contrast to the 2-unit FPD, the maximum principal stresses observed in the 3-unit FPD model, under pontic only axial loading, were located within the connector between the pontic and the adjacent retainer. The stresses in the cervical region of the distal retainer were lower in the 3-unit FPD model than those observed in the 2-unit FPD model, indicating that the distribution of maximum principal stresses under axial loading of the pontic only

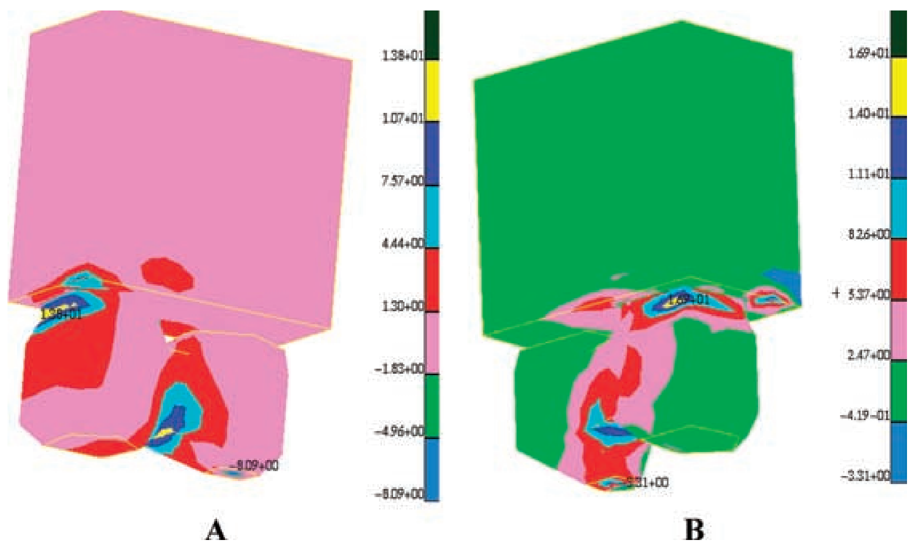


Figure 5. Maximum principal stress distribution: (*A*) 50 N applied axially to the pontic only (buccal view); (*B*) maximum principal stress distribution under 50 N applied laterally to the internal slope of the buccal cusp of the pontic only (lingual view).

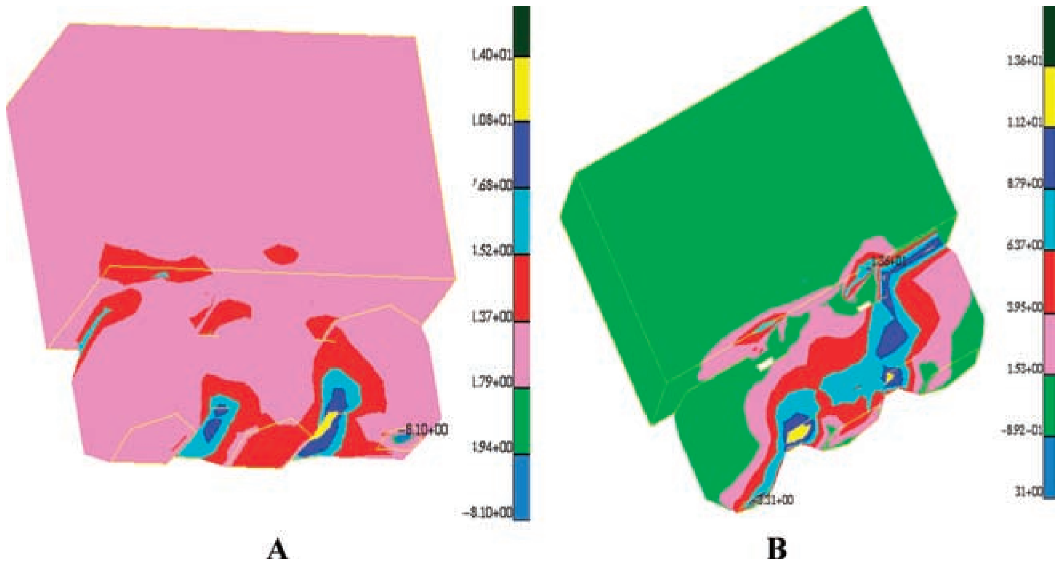


Figure 6. Maximum principal stress distribution: (*A*) 50 N applied axially to the pontic only (buccal view); (*B*) 50 N applied laterally to the internal slope of the buccal cusp of the pontic only (lingual view).

could be considered to be more favorable in the 3-unit FPD.

Lateral occlusal loading in the model of the 3-unit cantilevered FPD resulted in both lower maximum principal stresses and more favorable distribution of stresses than those observed in the model of the 2-unit FPD (Fig 6B).

Observed in sections under various loading scenarios, the 2 models indicated that the highest maximum principal stresses tended to be concentrated within the periodontal ligament and the connectors in both designs of the FPDs; pontic only loading generated the highest levels of stresses (Fig 7A). Distribution of stresses under same

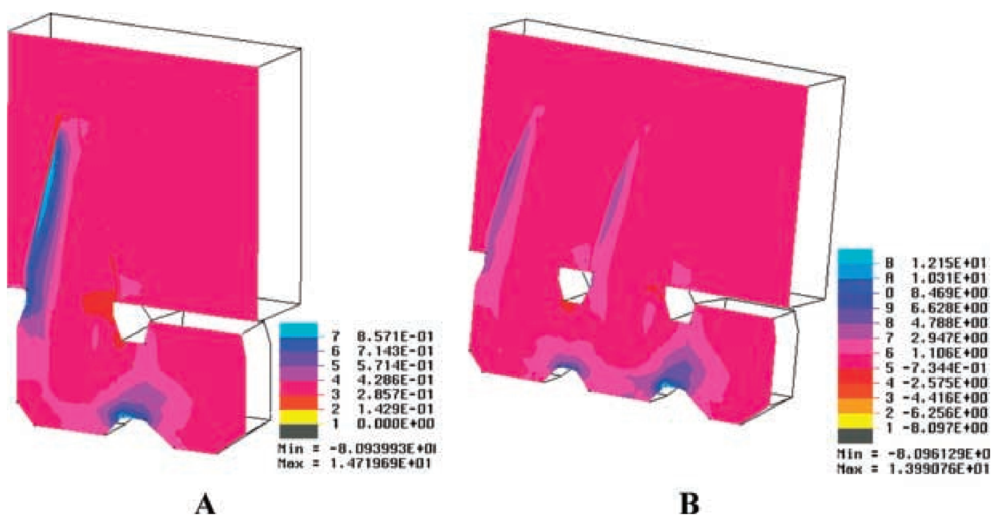


Figure 7. Maximum principal stress distribution: (*A*) mesiodistal section of the 2-unit FPD under 50 N applied axially to the pontic; (*B*) mesiodistal section of 3-unit FPD under 50 N applied axially to the pontic only.

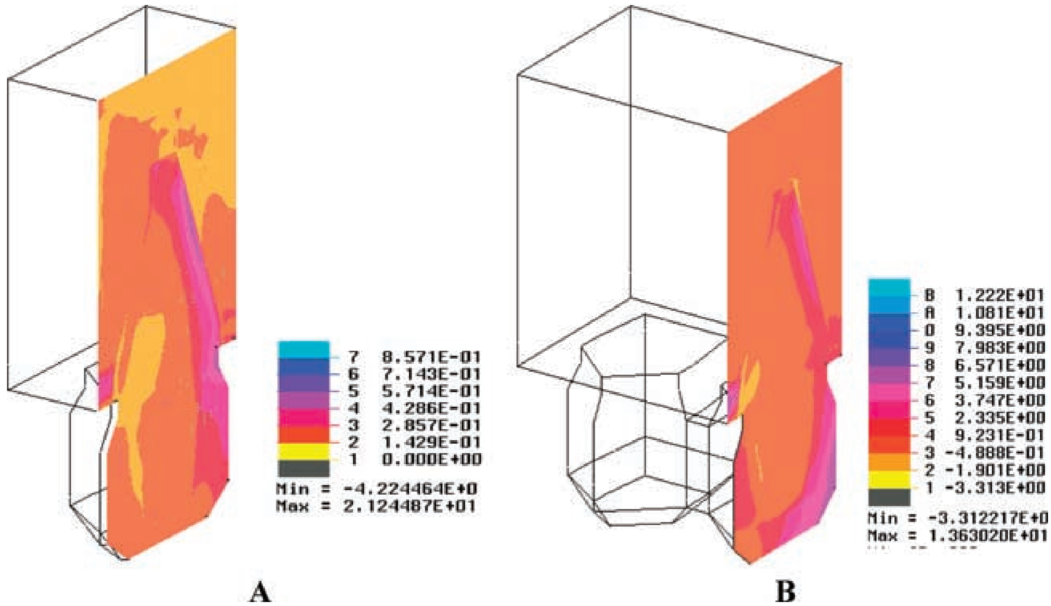


Figure 8. Maximum principal stress distribution: (*A*) buccolingual section of the 2-unit FPD under 50 N applied laterally to the internal slope of the buccal cusp of the pontic only; (*B*) buccolingual section of the 3-unit FPD under 50 N applied laterally to the pontic only.

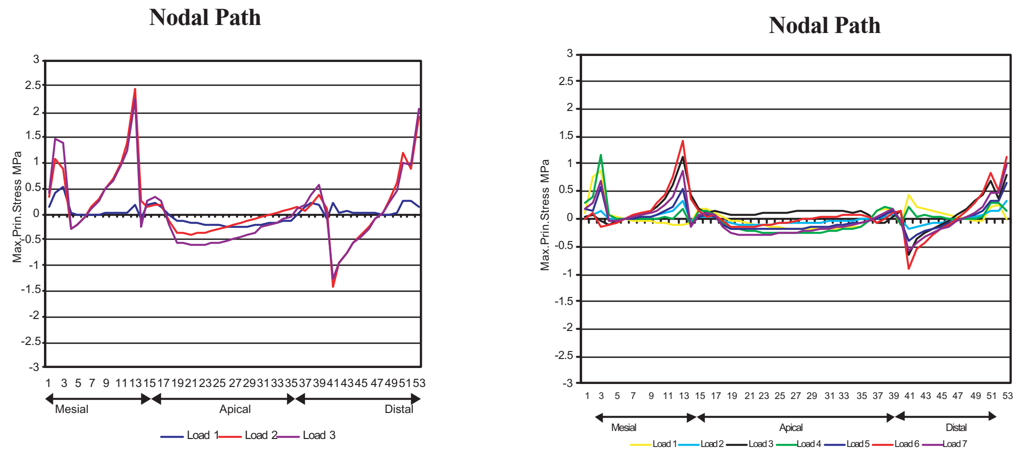
loading was less favorable in sections of the 2-unit FPD model compared with similar sections of the 3-unit FPD model (Fig 7B). Such differences were most apparent under lateral occlusal loading scenarios (Figs 8A and B).

No appreciable differences were observed in the maximum principal stresses in the periodontal ligament/bone and abutment/retainer interfaces between the 2- and 3-unit cantilever FPD models (Figs 9 and 10). The maximum principal stresses in the interfaces tended to be lower in the 3-unit cantilever FPD than those in the interfaces in the 2-unit cantilever FPD models, particularly in the cervical margin of the distal abutment of the 3-unit cantilever FPD (Figs 11 and 12).

Discussion

The present investigation, as one of a series on aspects of SDA therapy, has used FEA to compare and contrast the biomechanics of 2 cantilevered FPD designs for the replacement of a missing maxillary canine. Despite the sophistication of the finite element method employed, and various studies having validated the use of such techniques in the investigation of the biomechanics of dental restorations,[16] it is acknowledged that the analyses performed suffer a number of important limitations. Some of these limitations resulted from the assumptions made about the properties of the materials and tissues forming the finite element models, application of 50 N loading only,[17] and the loading scenarios investigated lacking the complexity of loading, which occurs in function in the patient. It is suggested, however, that the observations have relevance to a better understanding of the biomechanics of alternative designs of FPDs and that the findings may be applied, with caution, in further developing an evidence-based approach to FPD design.

The replacement of a missing maxillary canine, whether it be in SDA therapy or some other form of prosthodontic care, is a demanding challenge, notably in terms of securing the best long-term clinical outcome of cantilevered FPDs.[18] The present study was limited to 2 cantilevered FPD designs and as such has a relatively narrow scope. Related studies in the present program of research investigate the use of other FPD designs and the use of implants in the replacement of a missing maxillary canine. Collectively, these studies are anticipated to provide an extensive source of information on the biomechanical aspects of



A B

Figure 9. Variations in the maximum principal stresses along the periodontal ligament/bone interface under different scenarios of loading; (*A*) around the maxillary first premolar in the 2-unit FPD; (*B*) around the maxillary second premolar in 3-unit FPD.

the restorative options for the replacement of missing tooth units, with special emphasis on SDA therapy.

It is suggested that the findings presented indicate that inclusion of the second maxillary premolar in a cantilever FPD for the replacement of the missing maxillary canine may result in 40% less displacement under axial loading and 60% less displacement under lateral loading, when compared to the biomechanics under similar loading of the alternative 2-unit cantilevered FPD.

Increasing the number of abutments, and thereby the support for a cantilevered FPD, to replace a missing maxillary canine may therefore be considered to have biomechanical advantages. This view is supported by the more favorable distribution of maximum principal stresses observed in this study in the 3-unit FPD model, compared to those in the 2-unit FPD model. Locating maximum principal stresses away from critical margins, albeit in potentially vulnerable connectors, is believed to be an advantage in terms of potential longevity and reduced susceptibility to

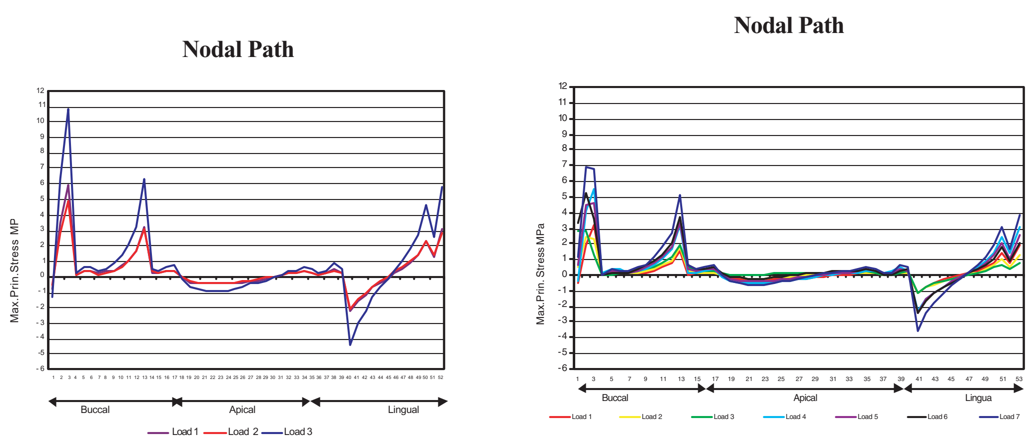


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Figure 10. Variation in the maximum principal stresses along the periodontal ligament/bone interface under different scenarios of lateral loading: (*A*) around the maxillary first premolar in 2-unit FPD; (*B*) around the maxillary second premolar in 3-unit FPD.

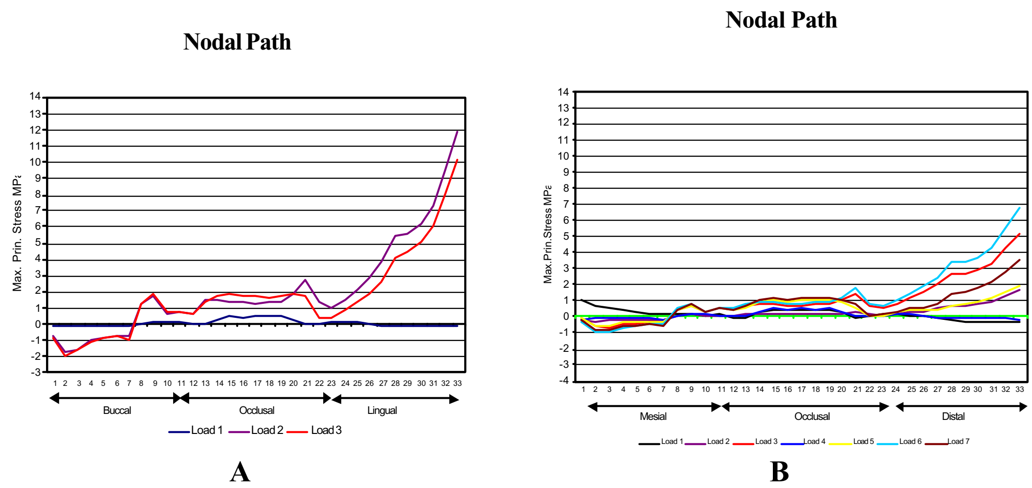

Figure 11. Variations in the maximum principal stresses along the retainer/abutment interface under different scenarios of axial loading: (*A*) around the maxillary first premolar in 2-unit design; (*B*) around the maxillary second premolar in 3-unit FPD.

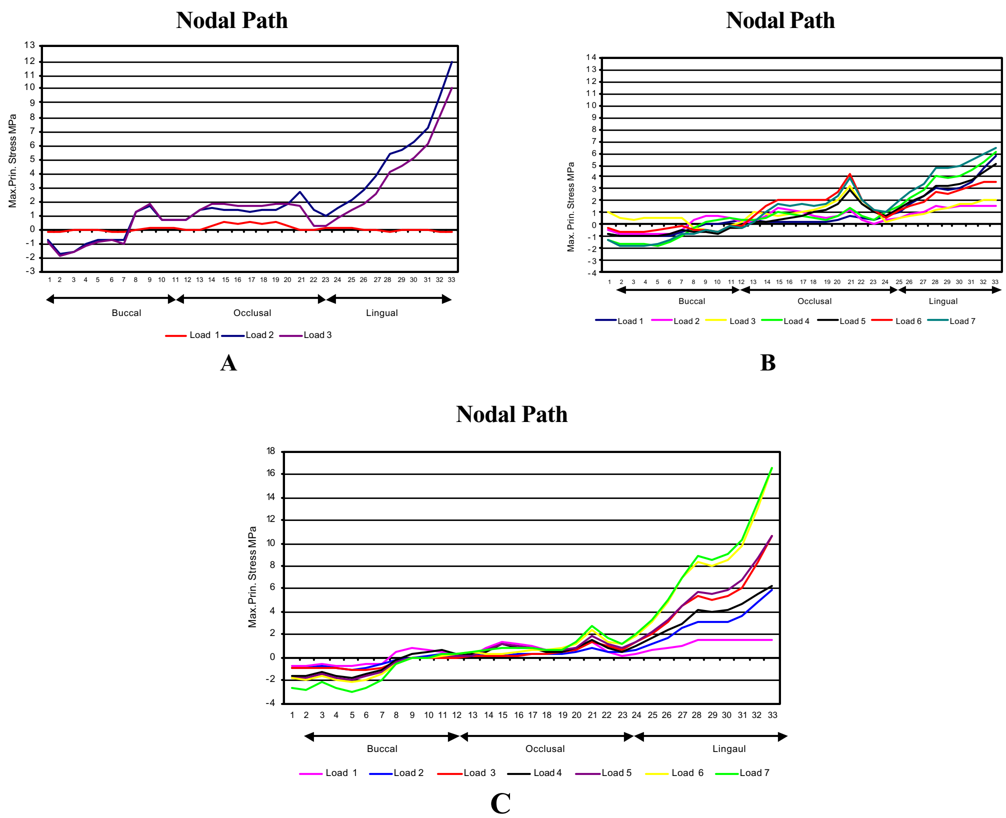

Figure 12. Variations in the maximum principal stresses along the retainer/abutment interface under the different scenarios of lateral loading: (*A*) around the maxillary first premolar in the 2-unit FPD; (*B*) around the maxillary first premolar in 3-unit FPD; (*C*) around the maxillary second premolar in the 3-unit FPD.

secondary caries; one of the most common causes of restoration failure in clinical service.[18] Such advantages must, however, be weighed against the disadvantages of including a second abutment in the FPD.

The maximum principal stresses observed in the present study are not as high as those reported elsewhere.[19,20] The use of 3-dimensional rather than 2-dimensional FEA, subtle differences between methods in modeling, and differences in assumptions about the properties of the materials and tissues forming the models may explain this. Commonality of approach to modeling by workers in the field would facilitate the comparison of findings from different centers; however, attempts to establish consensus in approach and shared methods in FEA in relation to dental restoration would require considerable work beyond the scope of the present study.

It is speculated that the differences observed between the stresses generated by axial and lateral loading would favor the creation of group function rather than canine guided occlusal scheme in a rehabilitation involving the replacement of a missing maxillary canine. These findings support conclusions drawn from longitudinal clinical studies of cantilevered FPDs.[21,22] The reduction of stresses in the periodontal ligament of 3-unit cantilevered FPD, as found in the present investigation, may outweigh the disadvantages of including an additional abutment in the prosthesis in those SDA patients who may be most prone to the progression of uncontrolled periodontal diseases. As in all prosthodontic care, a very large number of interrelated factors must be taken into account in working toward selecting the design of FPD best suited to individual patient needs and most capable of producing the best possible long-term clinical outcome in specific situations. Having decided on a design of FPD, this study indicates the importance of an understanding of the biomechanics of FPDs in planning and completing the necessary preparations. Knowledge of the possible areas of high stresses in FPDs under loading may aid more effective selection and preparation of the abutments.

The maximum principal stresses observed in the periodontal ligament/bone and abutment/retainer interfaces emphasize the importance of limiting lateral loading as part of the planning of the occlusal scheme and function of the FPD. This may be found to be of particular importance in SDA therapy in which molar occlusion may have been lost or at best compromised. Related studies in progress will further develop key biomechanical principles in FPD therapy.

Conclusions

1. 3-unit cantilevered FPDs replacing maxillary canines better distribute axial and lateral occlusal forces than 2-unit FPDs of similar design.

2. Displacement and functional stresses in cantilever FPDs to replace a missing maxillary canine may be minimized by reducing lateral loading and avoiding pontic only loading.

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