doi: 10.1111/j.1365-2591.2006.01085.x

A finite element analysis of ferrule design on restoration resistance and distribution of stress within a root

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Abstract

Ichim I, Kuzmanovic DV, Love RM. A finite element analysis of ferrule design on restoration resistance and distribution of stress within a root. *International Endodontic Journal*, **39**, 443–452, 2006.

Aim To analyse the effect of ferrule height upon the mechanical resistance and stress distribution within a root to explain variations in the pattern of root fracture.

Methodology An extracted, intact, caries free, maxillary right central incisor was scanned by laser and then reconstructed on a computer to produce a model of the tooth and associated periodontal ligament. A simulated post/core/crown restoration was constructed on conventional tooth preparations with various ferrules. The crown was loaded with a simulated 500 N force and the simulated displacement of components and the tensile and compressive stress within the tooth structure were recorded.

Results Without a ferrule preparation, the simulated crown tilted to the labial and rotated distally. With increasing ferrule height the displacement and rotation of the crown reduced in conventional and crown-lengthening models with maximum reduction occurring when the ferrule height reached 1.5 mm. In ferrule models, higher levels of tensile stress developed in internal (by a factor of 8) and mid-root palatal (by a factor of 90) dentine at the cervical margin of the preparation. With an increase in ferrule height, the area of tensile stress within the palatal mid-dentine expanded towards the cervical margin. Similar patterns and stress values were recorded for the crown-lengthening models.

Conclusion The study confirms that a ferrule increases the mechanical resistance of a post/core/crown restoration. However a ferrule creates a larger area of palatal dentine under tensile stress that may be a favourable condition for a crack to develop. Crown-lengthening did not alter the levels or pattern of stress within compared with conventional ferrule preparations.

Keywords: ferrule, post, root fracture, tensile stress.

Received 1 August 2005; accepted 9 November 2005

Introduction

A number of factors influence the functional life span of a restoration on a root filled tooth, these include the amount of remaining enamel and dentine, the properties of restorative materials and the design of the tooth preparation. After root canal treatment the functional and morphological integrity of a tooth is normally restored by an intracoronal restoration or fixed prosthesis (Sorensen & Martinoff 1984). If the amount of lost coronal tooth substance impairs retention of a fixed prosthesis, e.g. a crown, a cast indirect post-and-core may be required to replace missing tooth structure and provide retention for the restoration. The main function of a post is to provide intracanal retention of the core/crown restoration and to distribute functional loadings to a larger area of the remaining coronal tooth structure and root, however it has been shown that a post does not strengthen the root (Guzy & Nicholls 1979).

It is generally accepted that when restoring a root filled tooth with a post/core and crown a ferrule design should be incorporated into the tooth preparation and crown. The ferrule design incorporates a crown with a 360° collar that surrounds the perimeter of the

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prepared parallel dentine walls and extends cervically to the shoulder of tooth preparation. This design enhances the mechanical resistance of the treated tooth by distributing forces on the remaining tooth structure (Tjan & Whang 1985, Barkhordar *et al.* 1989, Sorensen & Engelman 1990) and thereby minimising disruption of the integrity of the bond of the post/core or crown to the tooth and the potential for root fracture. The ferrule may also affect the pattern of root fracture in post/core restored teeth, from debonding of the post/core to vertical root fracture in nonferrule designs to oblique or horizontal root fractures in designs incorporating a ferrule (Barkhordar *et al.* 1989, Milot & Stein 1992, Ng *et al.* 2004).

Numerous studies have linked the ferrule design with various factors such as remaining dentine thickness and distribution (Tjan & Whang 1985), different designs of the cervical collar (Barkhordar *et al.* 1989, Sorensen & Engelman 1990), ferrule height and configuration (Sorensen & Engelman 1990, Libman & Nicholls 1995, Isidor *et al.* 1999) and post design and material (Saupe *et al.* 1996, Gegauff 2000), with ferrule height being identified as a critical factor to mechanical resistance. The aims of this study were to analyse the effect of ferrule height upon the mechanical resistance of a reconstructed tooth by Finite Element Analyses (FEA) and to correlate the different ferrule designs with stress distribution within a root in order to explain variations in the pattern of root fracture.

Materials and methods

In order to obtain clinically relevant FEA results, particular attention was given to an accurate computer reconstruction of a tooth. As the main focus was to assess the influence of the ferrule height, the mathematical models were represented in a consistent manner, maintaining the ferrule height as the unique geometry variable.

Three-dimensional model

An extracted, intact, caries free, maxillary right central incisor was scanned by a laser 3D scanner (Picza Pix-4, Roland Co., Osaka, Japan). Starting from the point cloud from the scan, the tooth was reconstructed on a computer (PIV 2.4 GHz; 2GB RAM, Windows XP, Microsoft Corporation, Redmond, WA, USA) using current reverse engineering techniques in a generic CAD package (Rhinoceros 3D; v.3. Robert McNeel & Assoc., Seattle, WA, USA). This technique resulted in a maximum dimensional deviation of the digital model to the real tooth of <100 μm.

Using clinical guidelines (Rosenstiel *et al.* 2001) the digital model was then altered to accommodate a custom made post and core and crown restoration. The diameter of the post at the cervical and apical sections was 1/3 of the diameter of the root and the post extended apically to 2/3 of the root length. The crown had a uniform thickness of 1 mm, except at the incisal edge where it was 1.5 mm and the margin of the shoulder followed the pattern of the cementoenamel junction (Fig. 1). A periodontal ligament (PDL) was modelled as a uniform 250-μm thick shell surrounding the root and finished 1.5 mm apical to the cementoenamel junction. The presence of the PDL was required to accurately reproduce constraints of the system and also to provide the tensile component as discussed below.

Ferrule design

From a starting point at the crown margin, which had no ferrule, four conventional ferrule preparations involving the simulated coronal dentine were produced at 0.5-mm intervals up to a height of 2 mm and at a constant 1-mm thickness of dentine (Fig. 2). To simulate a crown lengthening procedure, four models with similar dimensions were produced apical to the cementoenamel junction extending down the radicular dentine. In these cases the simulated crown margin extended down the root face and the level of the periodontal ligament was adjusted to the relevant length of the extended ferrule preparation.

The root was divided into two concentric areas around the post preparation to mark the inner- (adjacent to the post), mid- and outer radicular dentine and five stress reading sites were located at 3-mm intervals along each of these boundaries (Fig. 3). In order to accurately read the stress associated with a ferrule preparation, the cervical mid-dentine reading site was aligned to correspond to the angle between the ferrule and the cervical seat of the preparation.

Boundary conditions and materials

Tooth structures are normally subjected to loading within their elastic range and the goal of this study was to analyse the consequences of design changes to the ferrule preparation, hence static linear analysis was performed for each case. In a static linear study, all loads are applied slowly and gradually until they reach their maximal values, there upon the loads remain

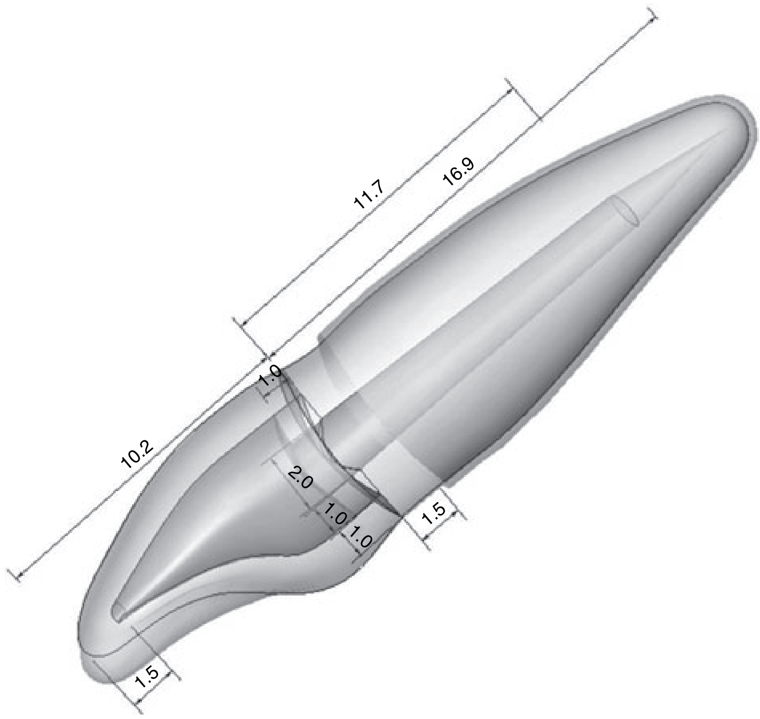

Figure 1 Sample image of the 1 mm ferrule model illustrating the dimensions of the model (millimetres).

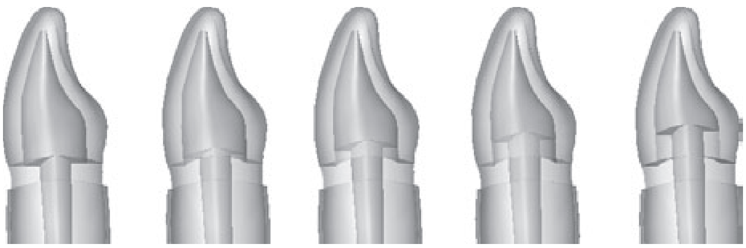

Figure 2 The five models demonstrating different coronal dentine ferrule height.

constant (time-invariant) and the FE calculation is made until the solution is convergent (no variation). The FE analysis was performed using a general purpose FEA package (Cosmos DesignStar 4.0; Structural Research and Analysis Corp., Santa Monica, CA, USA) using the computer as described above. The models were meshed using linear tetrahedral elements and in order to reduce the variability all the models were meshed using 600 μm elements. This resulted in an average of 27.000 elements per model (Fig. 4).

In order to simulate the effect of the inner socket wall, the models were fixed on the outer surface of the PDL with no rotation or translation allowed. The junction between the PDL and the external root surface was considered as bonded, while the contacts between all the other parts of the assembly were of a gap contact type. A gap contact condition allows the faces to move away from each other, while preserving the physical requirement of not penetrating each other. Also, to fully analyse the effect of the ferrule design, the friction coefficient between the different components of the assembly was set to zero, thus any displacement that occurred between the components was not restricted by friction. The material properties of the various simulated components were set in the solver (Table 1). To minimise variables between restorative materials, the properties of a nonprecious dental alloy were used for the post and core and also the crown. The PDL elastic modulus was based on the standard properties of a rubber (Saupe *et al.* 1996) and determined by a

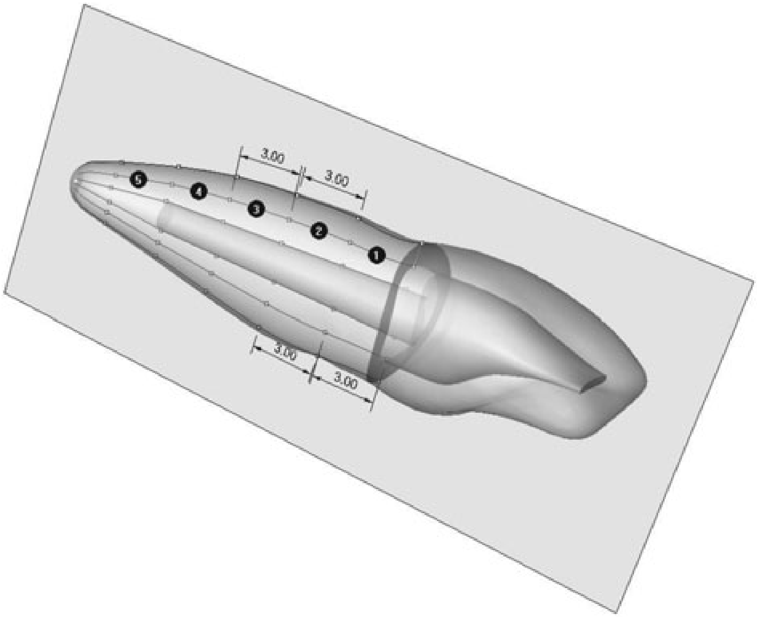

Figure 3 Representative diagram showing the boundaries of inner-, mid- and outer dentine and the location of the stress reading sites in these areas (numbers 1–5).

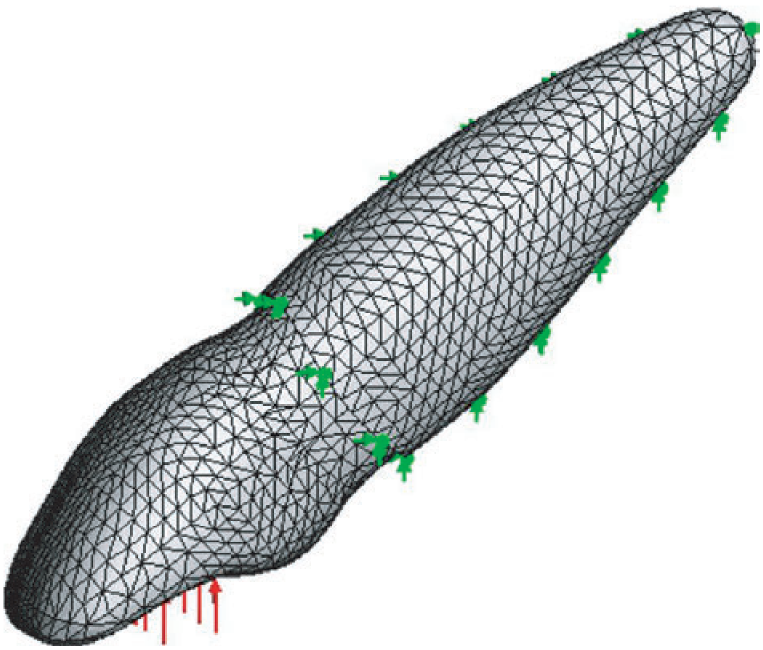

Figure 4 Meshed model demonstrating palatal surface loading area and restraints at external root surface.

preliminary test by steadily increasing the modulus of elasticity of the material, sourced from the software material library, until the vertical displacement of the simulated tooth under a 300 N axial load was 200 μm (Mühlemann 1960). This approach ensured that the elastic deformation of the material was within the physiologic range of the human PDL.

The crown was loaded with a simulated 500 N force directed at 120° to the longitudinal axis of the tooth onto a 5 mm^2 area of the palatal surface incisal to the cingulum (Milot & Stein 1992). This force corresponds to the upper range of occlusal load during function.

Post-processing

After the numerical input was created and the problem solved, the displacements and principal stresses were assessed. The principal stresses (σ_1 and σ_3) were used in

Table 1 Properties of materials used in FEA models.

Material	Elastic modulus (MPa)	Poisson ratio
Periodontal ligament	11.76	0.49
Steel	210 000	0.28
Dentine	14 700*	0.31

*(Sano *et al.* 1994).

the assessment because on one hand the root is made out of dentine, which is a brittle material and on the other hand, a comparison between the tensile and compressive stresses generated by each design allows a better understanding of the structure response. Although the study was not focused on predicting the system's failure, the principal stress determination can provide useful data considering that the maximum stress criterion states that failure occurs when the maximum (normal) principal stress reaches either the uniaxial tension strength or the uniaxial compression strength. Furthermore, the stiffness of the structures was compared by means of displacements calculated on the crown's incisal margin.

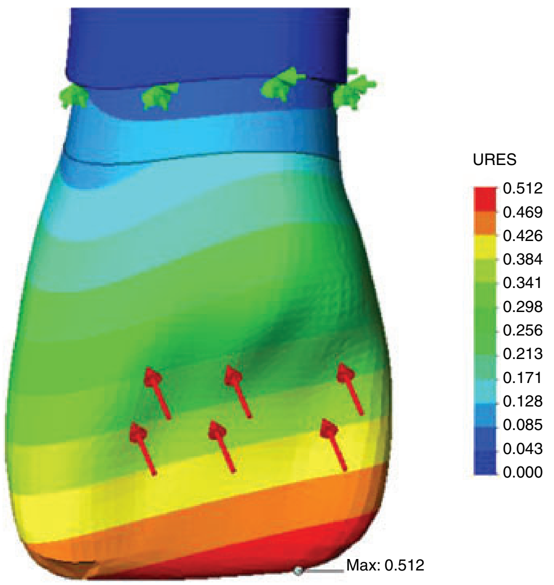

Figure 5 Image showing the point of application of the simulated force on the palatal surface with resulting uneven displacement of the crown seen as a rotation of the distal surface buccally.

Results

Displacement of the simulated crown

An analysis of the displacement of the simulated crown subsequent to the palatal force demonstrated that the crown tilted to the labial and rotated with the distal incisal angle being displaced more towards the labial compared with the mesial incisal edge (Fig. 5). This axial rotation may be due to the asymmetric shape of the cervical section or the morphology of the palatal surface.

The displacement values recorded at the midline of the palatal surface of the crown near the incisal edge and the maximal displacement at the distal incisal edge demonstrate that crown displacement reduced with increasing ferrule height up to 1.5 mm, after which there was no difference (Fig. 6). In the model a ferrule of, or >1.5 mm resulted in approximately a 35% reduction in displacement compared with the nonferrule preparation. The anti-rotational effect of the ferrule can be seen by the reduction in the difference between the maximum and mid-point displacement when a ferrule is present (Fig. 6).

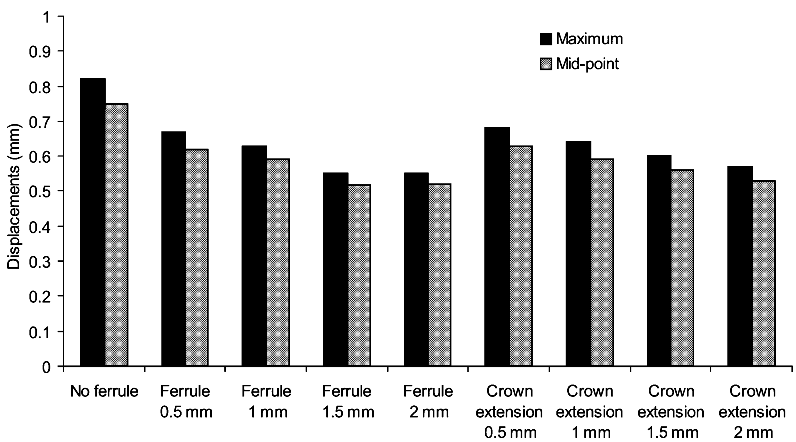

Figure 6 The effect of ferrule height on simulated crown displacement at the distal (maximum displacement) and mid-palatal incisal margin of coronal dentine ferrule and radicular dentine (crown extension) ferrule designs.

In the case of crown lengthening the crown displacement showed a similar trend, although the values were higher than the coronal dentine ferrules because of the increase in the length of the extracoronal arm (Fig. 6).

Stress analysis

Because of the direction of the force applied to the palatal surface of the simulated crown there was a tendency for the post to flex in a labial direction. This will result in a compressive stress developing in the labial dentine while the palatal dentine will be in tension as it is restricted by the periodontal membrane.

Tensile stress

Figure 7(a,b) demonstrates that when a ferrule was present, a higher level of tensile stress (σ_1) developed in internal and mid-root palatal dentine at the cervical margin of the preparation compared with a preparation with no ferrule. In internal dentine, the tensile stress for all models increased along the root to approximately the mid-root area, after which it decreased, with the stress being higher in models with ferrule preparations compared with no preparation (Fig. 7a). Compared with the values at the cervical area, the stress in mid-root palatal dentine was higher along the root when a ferrule was not present and less with all ferrule designs, with the values of the ferrule models similar to the nonferrule model (Fig. 7b). The tensile stress on the external palatal dentine was not influenced by the presence of a ferrule preparation (Fig. 7c).

A colour plot analysis showed that there were two peaks of maximal tensile stress on the palatal wall of the root at the junction between the ferrule and the cervical margin of the preparation and the other located within the periphery of the root dentine in the cervical two-fifths (approximately 3–5 mm from palatal cervical margin of the restoration) (Fig. 8a). With an increase in ferrule height, the area of tensile stress within the palatal mid-dentine expanded towards the cervical margin creating an almost constant area under tension bridging the external two-fifths of the root from the palatal aspect of the ferrule (Fig. 8b). However, the maximum nodal stress values showed very little difference between the samples.

Neither did the crown lengthening alter the pattern of tensile stress in any area of the root (Fig. 9) compared with the standard models (Fig. 7b) nor were the stress values within the dentine differed between the standard and crown-lengthened models (Fig. 10).

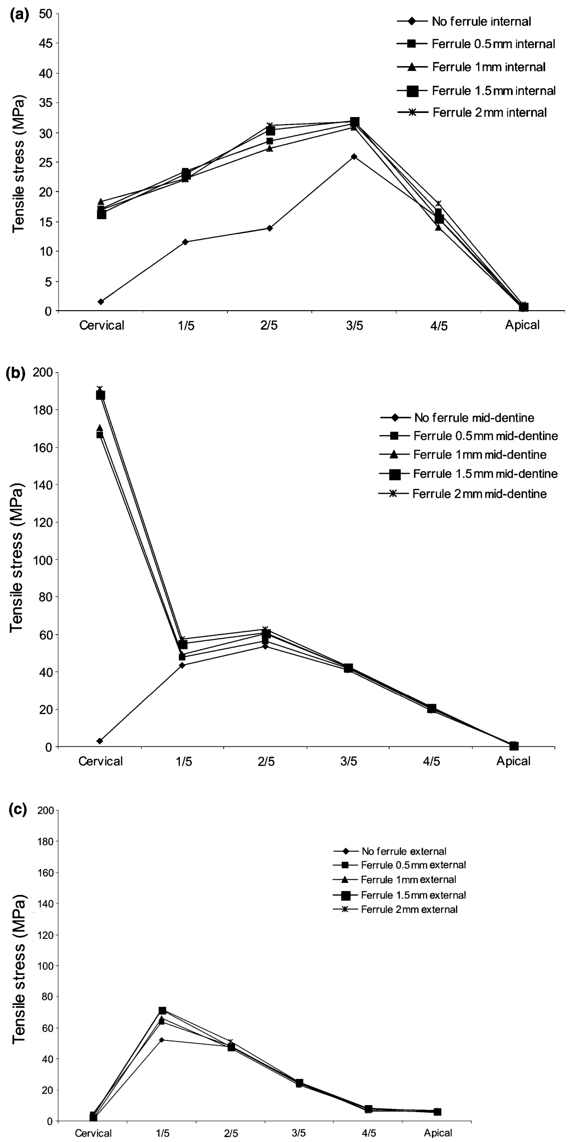

Figure 7 Plots of the tensile stress in palatal (a) internal dentine, (b) mid-dentine, (c) external dentine at the various recording points in the model.

Compressive stress

The presence of a ferrule resulted in a marked decrease in the σ_3 stress (compressive component) in the labial internal root dentine at the cervical measuring point, while the compressive stress at all other points for all models were similar (Fig. 11a). In contrast, on the labial external root dentine, there was very little

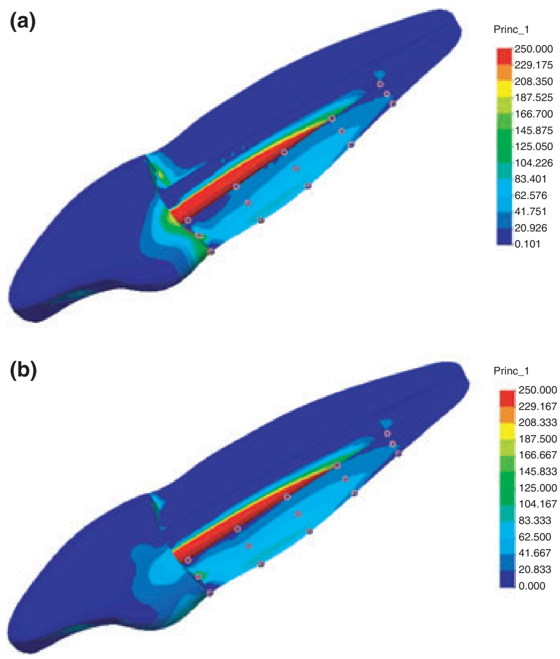

Figure 8 Colour plots of the tensile stress in (a) 0.5 mm ferrule and (b) 2.0 mm ferrule models demonstrating the extension of the area under tension with increased ferule height.

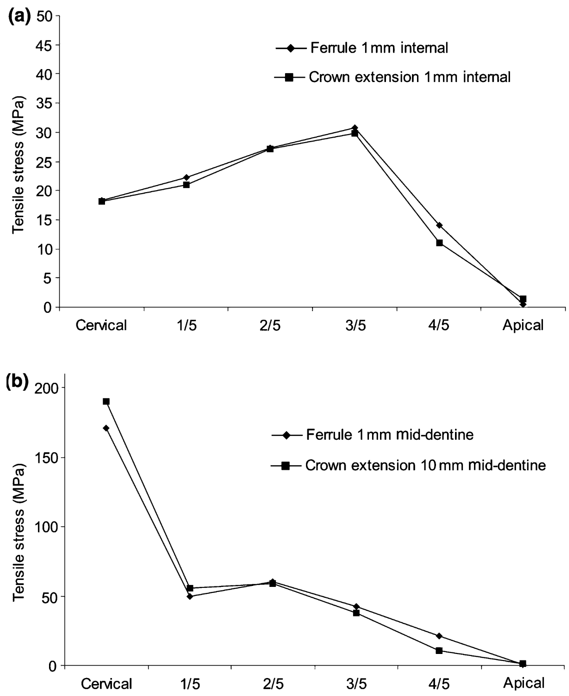

Figure 10 Tensile stress plots comparing stresses at (a) internal dentine and (b) mid-dentine in standard 1 mm ferrule and crown-lengthening models.

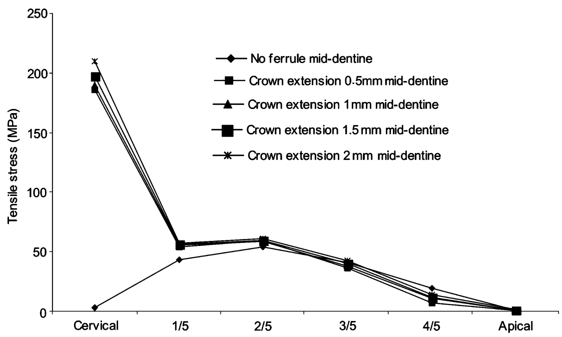

Figure 9 Plot of the tensile stresses in the palatal mid-dentine for the crown lengthening models.

difference in compressive stress, although there was a trend for reduced stress with increasing ferrule height (Fig. 11b). A similar pattern and stress values were recorded for the crown-lengthening models.

Discussion

An analysis of the displacement of components of a post/core/crown restoration can give some insight into the direction of forces playing on the restoration and tooth structure. In the absence of a ferrule preparation, an apical-labial directed force applied to the palatal aspect of a crown will produce a tilting force on the crown and core to the labial and an axial force that displaces the post/core occlusally, with the point of rotation below the contact point at a point along the labial shoulder of the preparation and the external root surface. As a result of the force and the limited compliance of the labial periodontal membrane, compressive stress develops in the labial dentine and in the palatal wall of the root canal at the apical extent of the post. The elastic restraint of the palatal periodontal ligament and direction of the force results in tensile stress generated within the palatal root dentine and within the post in its coronal aspect near the junction with the core (Fig. 12). In a clinical situation, these stresses will cause shearing stress on the luting cement and subsequent break down of the material, resulting in movement of the restoration and microleakage of oral fluids which will accelerate the mechanical failure of the restoration. The tensile stress values (Fig. 7) were

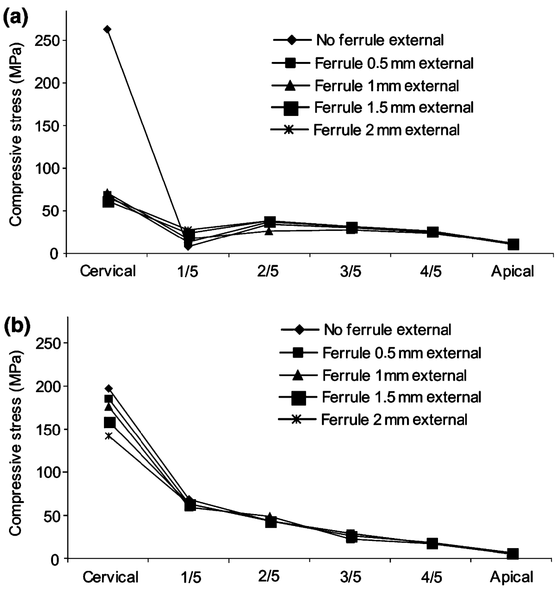

Figure 11 Plots of the compressive stress on the (a) internal and (b) external buccal root dentine.

much less than the tensile strength of dentine (185 MPa, Sano *et al.* 1994) and lower than compressive stress values (Fig. 11) suggesting that there is low risk of a crack initiating in the dentine, however once the post/core becomes loose the resulting lever action will favour fracture of the post in the coronal portion or the development of a vertical root fracture.

The results of the simulated crown displacement (Fig. 6) confirm that a ferrule preparation increases the mechanical resistance of the restoration (Tjan & Whang 1985, Barkhordar *et al.* 1989, Sorensen & Engelman 1990) by opposing displacement. This becomes most efficient when the ferrule height is greater than the rotation radius of the crown (Fig. 13). Although a short ferrule may not efficiently resist displacement, it does however reduce the axial arm of the rotation force and this results in reducing the bending force on the post with subsequent reduction of stress within the post and the axial displacement force. This reduces the potential for debonding of the lute and post-fracture.

There were two main changes in the stress distribution in root dentine associated with an increase in ferrule height, a decrease in compressive stress in labial cervical dentine (Fig. 11) at levels below the compressive strength of dentine (297 MPa, Craig & Peyton 1958) and an increase in tensile stress in palatal cervical dentine (Fig. 7a) to values approaching the

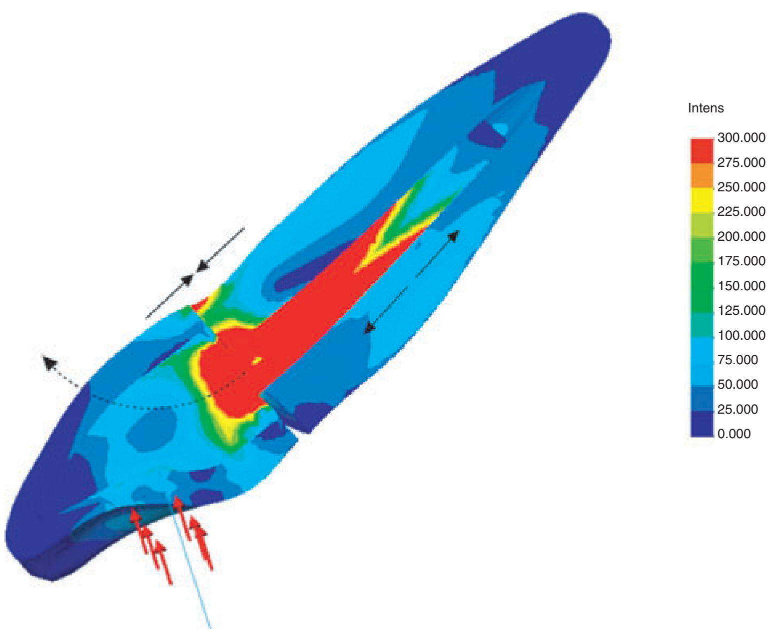

Figure 12 Diagram of a nonferrule model demonstrating the rotational movement that the post/core/crown will be subjected to under load (dashed arrow), the area of labial dentine under compressive stress (solid inward arrows), the area of palatal dentine under tensile stress (solid outward arrows) and tensile stress within the coronal portion of the post.

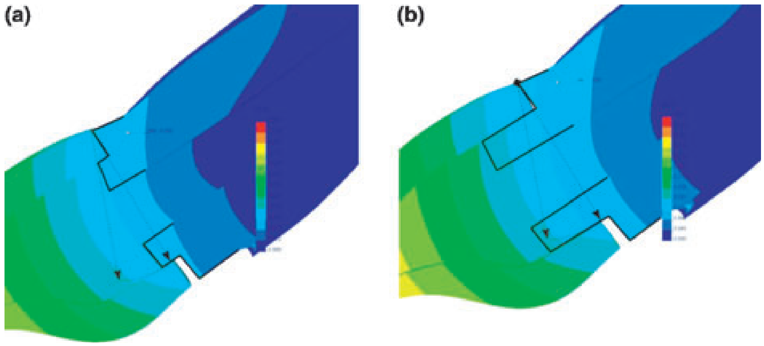

Figure 13 Diagram illustrating contact-induced displacement for (a) 0.5 mm and (b) 2 mm ferrule models. The arrows indicate the rotation radius of the crown and demonstrate that a 0.5 mm ferrule is less than the rotational radius of the crown while a 2 mm ferrule exceeds it and offers more mechanical resistance.

tensile strength of dentine (185 MPa, Sano *et al.* 1994) (Fig. 7b) with an associated increased area of palatal dentine under stress (Figs 8 and 14). This is probably due to the palatally applied force transmitting a flexing force to the palatal wall of the ferrule leading to the concentrated area of stress at the base of the palatal ferrule wall (Fig. 14). In the present study, the stress value in the cervical mid-dentine approached the tensile stress for dentine (Fig. 7b) suggesting favourable conditions for a crack to nucleate, which would run apically and obliquely along the palatal root dentine from the internal to the external root surface. These results may explain the mechanisms behind the different failure patterns observed by other researchers (Saupe *et al.* 1996).

Finite element models provide an insight into the processes involved when loading teeth but do not fully represent the clinical situation and limitations of the model should be recognised. For example in this model no alveolar bone was modelled and the model was fixed on the outside surface of the periodontal ligament so as to represent the effect of the inner socket wall and this may have resulted in higher stresses in the root. Similarly the elastic limit of the PDL was set at 11.8 MPa and modelled as an elastic material while recent work has shown that the PDL is visco-elastic with a modulus of around 1 MPa (Bourauel *et al.* 1999). In the present study, the PDL values were set so as to simulate the amount of displacement of a root that could occur clinically and the structural stresses were determined through the solid bodies (dentine, post and crown) of the model. As such a moderate change (increase of decrease) in the elastic modulus of the PDL would not alter the stress results inside the dentine, post and crown.

The results of the present study show that a simulated crown-lengthening procedure and ferrule preparation did not change the levels or pattern of stress within the models compared with conventional ferrule preparations and does not support the notion that crown-lengthening may result in a tooth with less ability to withstand load (Gegauff 2000), however methodology differences between studies may explain these differences.

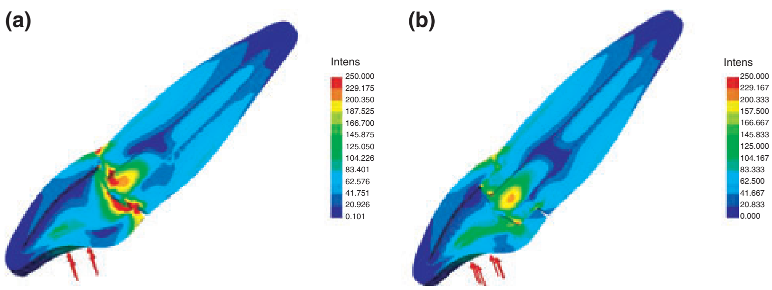

Figure 14 Diagram of the principle stresses in (a) 0.5 mm and (b) 2 mm ferrule models. Changes in the principle stress pattern with increasing ferrule height are evident as a decrease in compressive stress in labial dentine and within the root canal and increased area of tensile stress in palatal dentine especially around the palatal ferrule wall (the post has been removed for clarity).

Conclusion

Using FEA, the study shows that a ferrule increases the mechanical resistance of a post/core/crown restoration by reducing the potential for displacement (labial and axial rotation) and compressive stresses within labial dentine and the canal wall. The results suggest that the ferrule height should be determined individually for each case based on the bucco-lingual cervical diameter of the root. As a drawback the presence of the ferrule creates a larger area of palatal dentine under tensile stress, which may be a favourable condition for a crack to develop on the palatal aspect of the root eventually leading to an oblique root fracture. By comparison, a restoration without ferrule is prone to fail primarily by debonding and subsequently by root fracture through the lever action of the loose post. Crown-lengthening did not alter the levels or pattern of stress when compared with standard ferrule preparations.

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