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Application of finite element analysis in root canal therapy

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1. Introduction

Finite element analysis (FEA) is an engineering method for the numerical analysis of complex structures based on their material properties. It is used to determine the distribution of stress when a structure is subjected to force. Recently, FEA has been employed in endodontic. Endodontic diseases, such as pulpits or periradicular periodontitis, often require root canal therapy. During or after treatment, the pulpless teeth are more prone to fracture as an increasing amount of tooth structure is lost from disease or operative procedures.

An important cause of endodontic failure is vertical root fracture (VRF), defined as a longitudinal fracture confined to the root that usually begins on the internal wall and extends outward to the root surface (Walton 2002). VRF is an increasingly common cause of failure of tooth restoration. Beside the difficult diagnosis, the management often requires rather aggressive approaches, i.e., extraction or root amputation. Although a conservative approach has been suggested, the long-term outcomes are still questionable (Kawai & Masaka 2002, Trope & Rosenberg 1992).

It has been reported that approximately 0.2% of root filled teeth each year are lost directly because of VRF (Dammaschke *et al.* 2003, Fuss *et al.* 1999). Due to the high prevalence, poor diagnosis and prognosis of VRF, prevention is therefore of great importance. To avoid the problems caused by VRF, a full understanding of the etiological factors of root fractures is pivotal before preventive measures can be developed. Finite element analysis was first used more than 10 years ago to determine the factors that influencing fracture susceptibility. This chapter will focus on the contribution of finite element analysis to root canal therapy.

Root canal therapy and the use of intraradicular dowels are the two main iatrogenic factors associated with VRF. In root canal instrumentation, enlargement of the coronal third of the root canal space is considered important to support root canal length measurement, debris removal, and canal obturation. However, extensive use of rotary instruments, to be cut dentin to straight lines at curvatures during preparation of the canal space, weakens the root structure. With infected root canals especially, a balance should therefore be sought between the need to remove infected dentin and to maintain sufficient root thickness to withstand the forces of mastication. Special attention to securing sufficient remaining dentin should be given to the teeth and roots most susceptible to fracture, i.e., the maxillary and mandibular premolars and the mesial roots of the mandibular molars.

2. FEA of root canal instrumentation

2.1 Analysis of different conventional preparation techniques

Over decades, clinicians have promoted several preparation techniques for canal instrumentation. Here, we introduced three common techniques.

2.1.1 Instrumentation using the crown-down technique

In the crown-down technique, the clinician essentially works from the crown of the tooth to shape the canal towards the apex. For example, one may start from the coronal portion with gates gliddens that do the coronal flaring or initiate the coronal widening with a #35 K file. This file will only pierce a few millimeters into the coronal aspect of the canal, which is then widened carefully by the circumferential filing. Following this coronally initiated instrumentation, smaller files will penetrate ever deeper into the canal until the smallest files reach the root apex, and achieve a funnel shape.

2.1.2 Instrumentation using the step-back technique

In the step-back technique, the dentist instruments the apical portion first and then progressed toward coronal. Following the bulk removal of the pulp in the extirpation phase, small hand files are adopted nearest the apex. The dentist progresses to larger sizes of files and works back up the canal. A little bit more dentin is cut and removed by each file. Usually these advance about one millimeter with each new instrument. Subsequently the coronal portion of the root canal is conically shaped using the step-back technique through four additional instruments sizes. Finally, the original root canal obtains a funnel shape.

2.1.3 Instrumentation using the reverse-flaring technique (Yang *et al.* 2004)

In the reverse-flaring technique, emphasis is placed on flaring the coronal portion of the preparation before the completion of the apical portion. The dentist employs the hand instruments (files) destined for later apical instrumentation in a reverse order. Because the canal entrance is an anatomically determined narrowing, it is referred to as a "coronal constriction". Therefore, the early elimination of this constriction simplifies the subsequent instrumentation steps. "Reverse flaring" is performed in this coronal widening. After the coronal widening, the K file is adopted again to widen the apical portion. During the procedure of apical instrumentation of the root canal, the small files must be applied over a sufficient time. In curved canals, more effective preparation of the apical area will be made if the file has fewer obstructions in the coronal part.

2.1.4 Comparison of different conventional preparation techniques

As discussed above, different preparation techniques induce various canal morphologies. To assess the stress and fracture possibilities, Finite Element Analysis (FEA) has been used to estimate these preparation techniques.

Cheng *et al.* (2007, 2009) studied the stress distribution on endodontically-treated teeth with curved canals under various loads and determined the differences among three preparation techniques. They pointed out that the three techniques (crown-down, step-back and reverse-flaring techniques) displayed a similar stress distribution at the lower part of FEA model when occlusal loads and condensation loads were applied. In the case of vertical condensation, the maximum stress was close to the reported tensile strength of dentin. The warm vertical compaction technique was likely to result in root fractures when excessive compaction forces (50 N) were loaded. The FEA model also revealed a tendency toward stress concentration below the compacting level.

3. Root canal morphology after root preparation

There is reasonable evidence for the putative causal linkage between endodontic treatment and tooth fracture. Predisposing factors of root fracture of endodontically-treated teeth include altered physical properties of dentin, i.e., moisture loss in pulpless teeth, previous cracks in the dentin, loss of alveolar bone support, etc. However, based on both clinical and experimental studies, the main cause is considered to be changes in gross canal morphology, including loss of dentin thickness, altered canal curvature, and altered canal cross-section shape. It is likely that these factors interact cumulatively to influence distribution of stresses and tooth vulnerability to loading, ultimately increasing the possibility of catastrophic failure.

To discuss the relative contribution of geometrical parameters after root canal preparation to tooth fracture, FEA models have been constructed to analyze the stress distribution of teeth quantitatively after root canal preparation. By far, the most repeatedly discussed morphological parameters affecting stress distribution on modified FEA models are dentin thickness, radius of canal curvature, canal cross-sectional shapes, canal irregularities, and canal taper.

3.1 Dentin thickness

As reported in many clinical and experimental studies, the dentin thickness is in inverse proportion to the fracture susceptibility. Using FEA, Ricks-Williamson *et al.* (2009) found that the magnitude of generated radicular stresses was directly correlated with the simulated canal diameters. Wilcox *et al.* (1997) found that root surface craze lines formed on roots where greater percentages of the canal wall were removed.

Hong *et al.* (2003) constructed FE models of the mandibular first molar with diameter of root canal modified to 1/4, 1/3 and 1/2 of that of the root. They revealed that enlargement of the root canal resulted in an increased concentration of stress on the root canal surface at the orifice and coronal 1/3. In the lower part of the root canal, the stress distribution disparity smoothened out with the decrease of stress on the root canal surface.

Cheng *et al.* (2006) studied the stress distribution with FEA models of normal wall thickness (12 mm) and roots with 75% , 50% and 25%, respectively, of normal wall thickness. They found that the enlargement of root canal diameter increased the stress of the root canal wall up to 37% under lateral loading. Sathorn *et al.* built eight FE models indicating that the more dentin removed, the greater the fracture susceptibility. These results also concur with those reported by Wilcox *et al.*(1997).

In many clinical and experimental observations, the typical and most frequently observed vertical root fracture pattern is in a predominantly buccolingual direction, which occurs outwardly from the wall of root canal and through the thickest part of dentin.

Lertchirakarn *et al.* (2003a,2003b) also showed the non-uniform tensile-stress distribution is in a predominantly buccolingual direction, even though the dentin in this direction is typically thicker than in the mesiodistal direction. They constructed a series of FEA models with progressive reduction in proximal dentin thickness, which shows that decreasing proximal dentin thickness increased the tendency for buccolingual stress concentration and hence the predisposition to buccolingual fracture, but not the direction of maximum tensile stress.

This pattern is not expected by most because of the prediction that fracture is more likely to happen through the thinnest part of dentin. The authors explain the mechanism of this counterintuitive phenomenon is that when pressure is applied in a thick-walled vessel, stresses in the wall are of two types: tensile stress in a circumferential direction, and compressive stress in a radial direction. The thin part of the wall will be forced to expand more readily than the thick part of the wall in a radial direction. The asymmetrical expansion creates additional circumferential tensile stresses on the inner surface of the thicker areas, resulting from the outward bending of the thinner part of the dentin wall.

Sathorn *et al.* (2005a, 2005b) further demonstrated another less typical pattern of vertical root fracture: mesio-distal fracture pattern. Canal diameters of 1.0, 1.5, and 2.0 mm were created and the corresponding thinnest parts of dentin were 0.75, 0.5, and 0.25 mm, respectively. As canal diameters were increased in the models, the notional fracture load was correspondingly lower. When the dentin thickness decreases, the stresses are not concentrated specifically on the buccal and lingual aspects in the internal canal wall any more, the external surface stresses in the proximal area increase progressively, and the fracture pattern may change from buccal-lingual to mesio-distal.

However, reduced dentin thickness does not necessarily result in increased fracture susceptibility. Lertchirakarn *et al.* logically speculated that the reduction of the degree of the curvature inside the root canal could reduce fracture susceptibility and that changing the canal shape from oval to round actually relieves internal stresses despite the substantial thinning of proximal dentin. Sathorn. *et al.* proved that elimination of stress-raised areas, as in buccal and lingual extremities of ribbon shaped canals, reduces susceptibilty to fracture. These results suggest that the contribution to fracture susceptibility by loss of dentin thickness might be overwhelmed by other morphological parameters, i.e., canal curvature.

In conclusion, stress analysis data obtained by FEA indicates that, with a moderate preparation, dentin thickness is not a determining factor of fracture site or direction. However, with further loss of dentin, an increase of stress concentration occurs, and the vulnerability to root fracture is increased.

3.2 Radius of canal curvature

Knowing the severity of root canal curvature is essential to selecting the instrument and instrumentation technique. What is more, root canal curvature is also a determinant of the prognosis of instrumented teeth, taking a variety of reported complications (apical foramen, creation of ledges, elbows, zips, perforations, instrument fracture, and vertical root fracture) into consideration. Several FEA models have been constructed to discuss the relationship between the radius of canal curvature and stress distribution.

Lertchirakarn *et al.* (2003a) indicated that circumferential tensile stresses were concentrated on the buccal and lingual surfaces of the canal wall, corresponding to areas of greatest canal wall curvature, suggesting that the fracture initiates from the site of greatest curvature of the root canal wall and propagates to the outer root surface. FEA models demonstrated that changing the outer root shape from round to oval, with a round canal, resulted in a smaller increase in maximum tensile stress than changing the inner canal shape from round to oval, leading to the conclusion that canal curvature is more important than external root morphology, in terms of stress concentration.

Sathorn *et al.* (2005b) constructed an FEA model and modified the root cross-section to a smooth ovoid shaped canal to simulate the root canal preparation, resulting in the reduction of degree of curvature. In the model, the notional fracture load of 40 N was almost double that of the previous model. The stress pattern distribution was much more uniform than in the previous model, and highly localized stress was not found in any area other than the buccal and lingual canal walls. Thus, the fracture susceptibility is reduced.

According to previous studies, it is reasonable to conclude that a prepared root canal with an increased canal curvature radius reduces the stress concentration, and thereby, reduces fracture susceptibility.

3.3 Canal cross-sectional shapes and canal irregularities

Irregular canal cross-sectional shapes and canal irregularities are not only unfavorable factors in the operation of root canal therapy, but also compromise the prognosis of the treated teeth. Canal cross-sectional shapes include circular shape, oval shape, flat shape, and ribbon-shape canals. Canal irregularities include multiple foramina, additional canals, fins, deltas, intercanal connections, loops, 'C-shaped' canals and accessory canals. FEA models are constructed to simulate their influence on stress distribution in the studies described below.

When the canal shape is not circular, the stress distribution becomes asymmetrical. The tendency for highest stresses in a buccolingual direction was greater in the mandibular incisor, with its more pronounced oval root shape and ribbon-shaped canal shape, which suggests that VRF is not the direct outcome of hoop stresses uniformly distributed around the canal, but arises from asymmetrical stress concentrations, and that canal shape and localized irregularities in the canal wall may serve to raise stresses even further to the point of initiation of the fracture. A comparison of models which have the same external root shape showed that changing the canal shape from oval to round actually relieves internal stresses despite the substantial thinning of proximal dentin (Lertchirakarn *et al.* 2003a).

Sathorn *et al.* (2005b) constructed an FEA model with ribbon-shaped root canal and modified the root cross section to a smooth ovoid shaped canal to simulate the root canal preparation. The stress pattern distribution was then much more uniform than in the previous model, and highly localized stress was not found in any area other than the buccal and lingual canal walls. Thus, the fracture susceptibility was reduced.

By FEA, Versluis *et al.* (2006) also indicated that round canals showed lower uniform distributions, whilst oval canals showed uneven distributions with high concentrations at the buccal and lingual canal extensions and greater stresses in the coronal and middle thirds than in the apical third. After root canal preparation, round canals introduced only small circumferential stress increases in the apical half, while oval canals produced substantial reductions where the canal was enlarged to a smooth round shape. Even when fins were not contacted by the instrument, stresses within the root were more evenly distributed and reduced by up to 15%.

Round canal shape has long been proved to have more fracture resistance than that of oval canal shape. Moreover, canal shape as a morphological parameter brings about more profound changes to stress distribution than root shape. Elimination of canal irregularities is certain to provide a more evenly distributed canal stress.

3.4 Canal Taper

The prepared canal diameter has also long been proved to influence the propensity for vertical root fractures. Generally, taper should be sufficient to permit deep penetration of spreaders or pluggers during filling, but should not be excessive to the point where procedural errors occur, and the root is unnecessarily weakened. Holcomb *et al.* (1987) remarked that there must be a point at which increased canal width and taper begin to weaken the root.

To analyze the effect of the change of the tapers on the stress and the distribution on the root canal wall resulting from root canal preparation, Shi *et al.* established a three-dimensional finite element model of maxillary first premolar (single root and type Ⅳ root canal), then modified the model according to different root canal tapers after preparation. The maximum stress on the root canal wall and its distribution under vertical or lateral pressure were calculated, revealing that the enlargement of the root canal tapers after preparation can result in the rise of stress on the root canal wall, especially under lateral pressure.

Rundquist el al. (1983) constructed three FEA models of a root filled premolar tooth varying only in canal taper. The stress distribution in the root during the occlusal loading and filling was both recorded and compared with each other. During filling, root stress decreases as the canal taper increases, with generated stresses being greatest at the apex and along the canal wall. After root filling is complete and occlusal force is applied, the relationship is reversed. The generated stress is greatest at the cervical portion of the root surface, and increases slightly as taper increases. The authors concluded that it is possible vertical root fractures initiated at the apex are a result of filling forces, whereas vertical root fractures initiated cervically are a manifestation of subsequent masticatory events on the root filled tooth.

However, due to the complexity of relationship of taper and stress distribution (canal taper is in inversely proportionate to the generated stress value under filling forces while directly proportionate to the generated stress value under occlusal forces), and that the relative contribution of filling forces and occlusal forces to VRF remains illusive, further study is required.

3.5 Clinical suggestions

Many morphological factors (dentin thickness, radius of canal curvature, canal shape and size, canal taper, etc.) interact with each other to influence fracture susceptibility and pattern, and any one variable can easily predominate over the others.

Stressing the significance of canal anatomy, Peters *et al.* reported that variations in canal geometry before shaping and cleaning procedures had more influence on the changes that occur during preparation than the instrumentation techniques themselves. However, endodontic and restorative procedures have been addressed as absolute precipitating factors for VRF. On that basis, the results from the previous reports provide an experimental foundation to better understand the morphological parameters affecting stress distribution after root canal preparation and their relative contribution to VRF, which are of great importance in the clinical practice of root canal preparation to prevent VRF.

Canal preparation should be as conservative as practical, consistent with adequate cleaning and shaping. A smoothly rounded canal shape is favorable and can eliminate stress concentration sites, which inevitably result in higher fracture susceptibility. Mechanical instrumentation of root canals can produce craze lines on the root canal wall, which may serve as locations of increased stress (in accordance with stress-concentration theory).

Instrumentation procedures should be undertaken with gentle force, using generous irrigation to avoid crazing. The dentist's goal should be to create a root canal shape that maximizes radius of curvature of the root canal wall. A circular shape minimizes stress concentration areas and will distribute stress more uniformly. Furthermore, procedural pitfalls that create stress concentration sites on the root canal wall, i.e., ledging, gouging, and crazing, should be avoided. Although canal cross-sectional shape seems more important than dentin thickness in stress distribution, removal of root dentin should be minimized. By maintaining dentin thickness as much as possible, especially in the proximal areas or in the thin part of root dentin, stress will be minimized.

4. FEA of Nickel-Titanium Rotary Instruments

In root canal therapy, instrument fracture is a potential consequence of canal instrumentation, especially when the instrument is bound at the tip. FEA has been employed to compare the stresses in a number of Nickel-Titanium Rotary instruments.

4.1 FEA in investigation of the mechanical properties of different NiTi rotary instruments

With the increased use of nickel-titanium (NiTi) rotary instruments for root canal therapy in endodontics, instrument fracture has become more and more prevalent. Extensive research has been carried out on the physical properties and mechanical characteristics of NiTi rotary instruments. Kim *et al.* (2008a) estimated the residual stress thereafter for some nickel-titanium rotary instruments (ProFile, ProTaper, and ProTaper Universal) using a 3-dimensional finite-element package. The simulation in the ProTaper design revealed that there was the greatest pull in the apical direction and the highest reaction torque from the root canal wall, while the least stress in occurred in the ProFile design. Stresses in ProTaper were concentrated at the cutting edge, and the residual stress reached a level that was close to the critical stress for phase transformation in the material. The residual stress was highest in ProTaper (see below for the ProTaper Universal and ProFile design).

Flexibility and fracture properties are determinant for the performance of NiTi rotary instruments. Kim *et al.* (2008b) evaluated geometrical differences between three NiTi instruments which affect the deformation and stress distributions under bending and torsional conditions. ProFile, with a U-shaped cross section, showed the highest flexibility among the three file models. The ProTaper, which has a convex triangular cross-section, was the stiffest file model. In the ProTaper, more force is required to reach the same deflection as the other models, and more torque is needed than other models to achieve the same amount of rotation.

Under torsion, all NiTi files showed the highest stress at their groove area. The ProFile showed the highest von Mises stress value under the same torsional moment whereas the ProTaper Universal showed the highest value under the same rotational angle. Additionally, the assessment of the stress distributions of three NiTi instruments with various cross-sectional configurations under bending or torsional conditional showed that ProTaper has the lowest flexural rigidity of all if a U-shaped groove is incorporated in the middle of each side (Kim *et al.* 2008b, 2009).

4.2 FEA in investigation of the parameters contributing to instrument failure

4.2.1 The radius and the position of the canal curvature

By FEA, Necchi (2008) investigated rotary endodontic instruments and demonstrated the usefulness of the finite element method in simulating the mechanical behaviour of these instruments during root canal preparation. The results indicated that the radius and the position of canal curvature are the most crucial parameters that determined the stress in the instrument, in that higher stress levels are produced by decreasing the radius and moving from the apical to the mid root position. The most demanding working conditions were observed in canals with sharp curves, especially in areas in which the instruments had larger diameters. To prevent the possible damage to instruments and fracture, it is suggested that the instruments should be discarded following their use in such canals.

4.2.2 Cross-sectional design of Nickel-titanium instruments

As NiTi instruments are generally perceived to have high fracture risk during use, new designs with lower fracture risks have been marketed. However, these design variations may also alter the forces distribution on a root during instrumentation and increase the potential dentinal defects that predispose to fracture.

Previous study (Kim *et al.* 2009) has indicated that, in Nickel-titanium instruments with rectangle-based cross-section, higher stress differentials are created during the simulated canal shaping, and higher residual stress and plastic deformation occurs than in instruments with triangle-based cross sections. It has also been shown that different cross-sectional designs affect stress distribution in NiTi instruments during the bending, torsion and simulated shaping of a curved canal.

For three NiTi file designs ProFile (U-shaped cross-section and constant 6% tapered shaft), ProTaper Universal (convex triangular cross-section with notch and progressive taper shaft), and LightSpeed LSX (noncutting round shaft), the stress conditions during the rotary instrumentation in a curved root were also estimated (Kim *et al.* 2010). ProTaper Universal introduced the highest stress concentration in the root dentin and also had the highest tensile and compressive principal strain components in the external root surface. ProTaper Universal had the biggest taper shaft and the calculated stress values from ProTaper Universal approached the strength properties of the dentin. LightSpeed generated the lowest stresses. It can be concluded that the stiffer file designs created higher stress concentrations in the apical root dentin during the shaping of the curved canal, which increases the risk of dentinal defects that may lead to the apical root cracking.

5. FEA of root canal compaction

Teeth with root canal treatment seems to be more susceptible to vertical fracture (VRF) than those with intact pulp. As well, it has been speculated that excessive pressure during the gutta-percha compaction process could lead to root fractures. Meister *et al.* investigated 32 clinical cases of vertical root fractures and postulated that the use of excessive force during canal obturation was the primary cause of these fractures (Meister *et al.* 1980). Studies showed that a spreader load as small as 1.5 kg might produce fracture during lateral compaction in extracted teeth (Holcomb *et al.* 1987, Pitts *et al.*1983).

FEA was also conducted to estimate the stresses that occurred during compaction procedures. Several results revealed that vertical compaction led to greater stress than lateral compaction. The maximum stress of vertical condensation was close to the reported tensile strength of dentin (50N), but still lower than the load required to fracture the roots (Cheng *et al.* 2009). The maximum stresses in the root dentin primary emerged during the first gutta-percha increment, afterwards, moved coronally with full condensation of successive gutta percha cones (Silver-Thorn *et al.*1999, Rundquist & Versluis 2006). These results lead us to believe that compaction technique when performed skillfully, does not likely create premature root fractures. Thus, obturation should not be regarded as a major cause of VRF, except in very weak roots (Lindauer *et al.* 1989).

Moreover, other factors can be addressed. These factors potentially include the direction and position of force loaded, root canal taper, final canal shape, number of gutta percha cones, the condition of supporting tissues, damping properties of dental gutta-percha, as well as thermal distribution during compaction.

5.1 The distribution of stress during vertical and lateral compaction

It has been long debated whether excessive application of pressure during compaction could result in root fractures. There have been efforts to understand stresses distributed throughout the curved or straight root canal during the application of different compaction techniques.

For lateral compaction, various standpoints exist for ages, regardless of produced stress magnitude or concentration area. Harvey (1981) noted that throughout condensation, the stress was concentrated in the middle third of the tooth root and moved coronally with full condensation, which coincided with the previous study made by Silver-Thorn (1999). However, Telli *et al.* (1998), consistent with Gimlin *et al.* (1986), showed that lateral loads led to a stress concentration area limited to the apical third of the tooth root. The results above-mentioned were conducted in the straight canal roots. For the curved root canal, the maximum lateral stresses were located in the loading site. The reason why the results appeared such a big difference may account for the diverse of model baseline.

For vertical compaction, a study showed that it led to greater stress than lateral compaction (Cheng *et al.* 2009). The magnitude of stress was close to the reported tensile strength of dentin, which was likely to cause root fracture. It is suggested that inadvertent undue force should not be applied during warm vertical condensation.

5.2 Effect of canal tapers on root stresses during obturation

It has been postulated that the prepared canal diameter may influence propensity for vertical root fractures. It is reasonable to speculate that increasing the taper of the canal preparation by removing more dentin from the canal wall would diminish the structural integrity of the root. Holcomb *et al.* remarked that there must be a point at which increased canal taper begins to weaken the root and might predispose a root to vertical fracture (Holcomb *et al.* 1987). Ricks-Williamson *et al.* found the magnitude of generated radicular stresses to be directly correlated with the simulated canal diameters (1995).

Recently, one investigation was designed to evaluate the effect of different canal tapers on stress distributions to determine whether vertical root fractures occurred at the time of filling or at a later time. The results showed that the stresses tended to be higher closer to the load site, and gradually decreased along the root canal wall until they increased again at the apical constriction during filling; whilst the highest stress levels were obtained during the first gutta-percha increment and became lower with subsequent increment. However, during the application of the post-filling load, the highest stresses were generated at the external root surface, especially concentrating at the cervical third. Furthermore, with increasing taper, root stresses decreased during root filling but tended to increase with post-filling load. It seems that root fracture derived from at the apical third is likely initiated during obturation, while fracture rooting in the cervical portion is likely caused by occlusal loads. Thus, this emphasizes the need to use moderate compaction forces during the first increment in order to reduce the risk of apical fracture.

5.3 Effect of damping properties on fracture resistance of root filling

It has been well established that the damping properties of the periodontal ligament are the main contributors to reducing the induced strain in a loaded tooth. Yet, other damping materials lie in the teeth, such as dental pulp. Huang *et al.* confirmed that dental pulp was in the nature of the cushioning effect to affect the stress distribution during an impact (Huang *et al.* 2005). A further study (Ou *et al.* 2009) showed that the stress reduction effect in the root filled model was lower than in unprepared intact teeth, but higher than in pulpless teeth. In addition, the stress reduction effect in intact teeth was lower on the loaded than on the opposite side, which may account for why dental pulp can disperse the strain energy and hence reduce the concentrated stress, because of the strain propagation passing through pulp tissue.

It is suggested that the damping properties should be taken into consideration during canal obturation. Dental gutta-percha of a favorable cushioning effect should be better developed in the future.

5.4 Finite element analysis of the thermal distribution

Nowadays, warm vertical compaction is a widely used technique. However, the use of the technique may lead to an unconscious transmission of excessive heat to the surrounding tissues, which may cause irreversible injury to tissues. The use of peak temperature should be well defined.

FEA is the right choice for thermal distribution evaluation, on account of its detection not only for root surface temperature, but also internal distribution of heat. Özgür Er *et al.* established a model of maxillary canine to determine the distribution and level of temperature (2007).

When used with a 200°C initial setting, simulated in a process involving seven stages and lasting for 34 seconds, the maximum temperature lying in gutta-percha is 56.6°C and the periodontal ligament temperature is between 37.3°C and 39.7°C. And the maximum temperature rise was observed at the apical tip of the simulated heat source. It has been reported that alkaline phosphatase is rapidly inactivated at 56°C, which is considered as the critical temperature for bone damage (Matthews & Hirsch 1972). Thus, 200°C as the initiative temperature created no potential harm to the tooth structure and the surrounding tissues.

In brief, although various standpoints exist during filling, those with the highest stresses were in: (a) the apical third; (b) the loading sites; (c) canal with smaller taper; (d) the canal surface; and, (e) during the first gutta-percha increment. In addition, apart from detecting the distribution of stress, FEA also highlights a large variety of filling procedures, and very accurate simulations can be conducted to investigate what might occur during compaction.

6. Other factors of tooth or periodontal tissue that influence stress distribution

Even though most of the factors contributing to VRF can be prevented by moderate root canal preparation and obturation procedures, still, there are dental and periodontal situations (morphological or pathological), such as oval shape root , proximal concavity, diminishing bone support, internal resorption, root perforation and periapical lesions that are partially responsible for unbalanced stress distribution in the root canal, and which lead directly to root fracture.

6.1 External root morphology

External root morphology, together with root shape are basic factors affecting stress distribution in the root canal wall and external root surface, which further affect the fracture susceptibility of teeth. However, canal shape seemed to be a more substantial factor than the outer root shape.

Lertchirakarn *et al.* (2003a) constructed a series of FEA models. The original model was a simple, thick-walled cylinder with little resemblance to any human tooth root. With progressive changes in inner and outer surface shapes and the reduction in proximal dentin thickness, the final model resembled an idealized, single-canal, mandibular incisor. The results demonstrated that a markedly oval root shape is more susceptible to high stress than a more circular one, regardless of the canal shape, even though the root shape seemed to be of less importance.

Sathorn *et al.* (2005b) also investigated the role of external root morphology, specifically a proximal concavity in mesio-distal fracture susceptibility. In this study, a basic model with a proximal concavity on the mesial and distal root surfaces was created. Both mesial and distal external root surfaces were reduced by 0.2 mm at the mid proximal area, and the resulting root shape was then smoothed to incorporate the concavity into the overall root outline. However, a proximal concavity did not significantly reduce fracture susceptibility as expected, rather it heightened stresses at external proximal surfaces. The concavity in the proximal surfaces itself had very little effect on fracture susceptibility when compared with ordinary roots sharing the same dentin thickness. It was concluded that external root morphology has minor influences on stress distributions of root.

6.2 Teeth with curved roots

Curved roots are another impediment in canal preparation. This is especially true near the apex of maxillary lateral incisors and the palatal root of maxillary first molars. Small, flexible instruments with non-cutting tips negotiate these curves, but larger, stiffer instruments start a ledge that can develop into a perforation. Furthermore, the risk of iatrogenic mishaps increases because root canals tend to be closer to the inner (concave) part of curved roots.

Cheng et al (2009) investigated (by FEA) the stress distribution within roots having curved canals when prepared by three preparation techniques. Three models of preparation by one of crown-down, step-back and reverse-flaring techniques (CDT, SBT and RFT) were established by replacing the inner canal, leaving the outline form unchanged to restrict the interfering factors. It was concluded that although the prepared canals varied in shape, little difference occurred in stress distribution around the root curvature and apex. The three preparation techniques had similar effects on simulated canals. After appropriate preparation, canals were enlarged and the stress increased to an extent below the tensile strength of dentin.

Lateral and vertical filling techniques were tested under occlusal loading, which revealed that vertical compaction led to greater stress than lateral compaction and excessive vertical compacting force (50 N) was likely to cause root fracture. Vertical compaction also produced a stress concentration area below the compacting level, which might be attributed to the anatomy of curved canal. Comparing the three techniques, RFT led to the least stress under lateral loads. As indicated above, RFT had combined features of both the CDT and SBT models, and as a result, it provided a thicker dentin wall around the curvature, reducing stress under different loadings.

Chatvanitkul *et al.* (2010) created 16 three-dimensional FEA models and estimated stress distribution in various degrees of curved roots with different post and restorations. The results indicated that the stress distribution pattern showed that degrees of root curvature (15, 30, and 45 degrees) had little effect.

The above studies show that degree of root curvature is not decisive to stress distribution; rather, the relevant preparation technique seemed more influential to fracture resistance of the curved root.

6.3 Teeth in pathologic state

Natural teeth with a healthy periodontal support exhibit stress transfer when functional forces are applied to them. These stress patterns show considerable variation during the pathologic state, which may influence both the tooth and supporting alveolar bone.

Telli *et al.* (1999) designed a maxillary canine tooth FEA model, based on a human cadaveric maxilla scanned by CT, in order to investigate the effect of pathological alterations of the dental structures (diminishing bone support, internal resorption, root perforation, periapical lesion). Patterns of stress distribution associated with pathological changes in dental structures were investigated. It was found that, diminishing bone support and internal resorption markedly increased stress magnitudes. However, it was mentioned that these values still remain much below the most frequently reported tensile strength of dentin (50-100 N/mm^2). This result led to the conclusion that when warm vertical compaction technique is skillfully performed and unwanted force is not applied, a premature root fracture in a large rooted maxillary anterior tooth with straight root canal anatomy is not likely to occur, even for the unfavourable conditions simulated.

The alveolar ridge's height of tooth was also studied by FEA, in order to simulate the pathological alternations of alveolar ridge and to analyze its effect on the stress distribution on the root canal wall (Hong *et al.* 2002). The height of alveolar ridge was modified by reducing 1/4, 1/3, 1/2 of the height. Lateral and vertical forces were loaded on the models. The modified models represented an increased stress concentration compared to the orifice of root canal, reaching the maximum in the coronal one-third. In models with different heights of the alveolar ridge, when the fixed height was lower, the decrease in stress concentration was less observable. This study indicated that reduction of alveolar ridge height (periodontal disease, periapical disease, etc.) results in increased stress concentration of the root canal, which, in the long run, will lead to root fracture.

Endodontic surgeries adopted to cure relating dental and periodontal pathological states showed considerable variation in stress patterns of the teeth before and after treatment, which may influence both the tooth and supporting alveolar bone.

Uensal E *et al.* (2002) applied FEA methods to evaluate variations in the stress under functional loads on first molars with periodontal furcation involvement, which were treated either with by root resection or root separation. This study used a two dimensional mathematical model of a mandibular first molar that was subjected to either a root separation or a root resection procedure. An evenly distributed dynamic load (600 N) was applied on two buccal cusps and distal fossae of the molar in centric occlusion. It was found that in the root resection model the stress values were maximum on the centre of rotation, and compressive stresses increased towards the middle of the cervical line. For the root separation model, the maximum shear stress values were observed in the distal portion, and a uniform stress distribution was observed in the mesial portion. Shear stress values for bone increased towards the centre in the bifurcation area.

Comparing to other factors that bring about VRF, the investigation of the influence of pathologic state seems scattered and the conclusions more diverse; moreover, the validation process of the FEA results remains absent. This situation is possibly the result of the many dental and periodontal states. More reliable FEA models are imperative to deal with these variations, and promote studies in this area.

7. The combination of two methods, FEA and fracture strength test, in stress analysis of vertical root fracture

7.1 Fracture strength test

Fracture strength test is an engineering discipline focusing on how and why fractures occur, and ultimately, the way to prevent or at least minimize the chance of fracture occurring. To get the general knowledge about dentin fracture mechanics and tooth fracture resistance, it is necessary to understand the biomechanical properties of dentin (Table 1).

	Young's modulus(GPa)	Poisson's ratio	References
Enamel	84.10	0.33	(Kampoosiora *et al.* 1994)
Dentin	18.30	0.31	
Pulp	2.07×10^{-3}	0.45	
Periodontal ligament	68.90×10^{-3}	0.45	
Cortical bone	10.00	0.30	
Cancellus bone	0.25	0.30	
Restorative material	3.00	0.24	(Lakes 2002)
Gutta-percha	9.30×10^{-4}	0.40	

Table 1. The values of Young's modulus of dental tissues

A study has revealed that the hardness values decreased in dentin closer to the pulp; and the authors concluded that the reduction in hardness was due to the increased tubule density and dentin porosity (Pashley *et al.* 1985). A subsequent study, however, demonstrated that the intertubular dentin near the pulp is highly likely to be less mineralized (Kinney *et al.* 1996).

Young's modulus, known as tensile strength, is another property of dentin. It is different even in the same tooth at different distances from the DEJ. Studies have shown that the Young's modulus of dentin tends to decrease with the distance from the DEJ toward the pulp (Kinney *et al.* 1996). But studies still have not found any difference of Young's modulus between vital and non-vital dentin.

Moisture content is another aspect that defines tooth mechanical properties. It is reported that decreased moisture content corresponded to increased tooth fracture susceptibility compared with vital teeth (Johnson *et al.* 1976). Therefore, reduced moisture content is considered a common reason for tooth vertical fracture in pulpless teeth. In teeth with pulp extirpation, fracture resistance can be reduced by 9% because of the progressive loss of moisture with time.

It is widely accepted that fracture can be classified as brittle and ductile and it involves crack formation and propagation produced by an imposed stress. To study the fracture susceptibility of roots, a specific testing machine was used in experiments to load roots to the point of fracture. However, because of the large variation of root shape, size and canal shape, size, the information about fracture susceptibility can be very difficult to assess statistically. Moreover, it is difficult to study the effect on fracture susceptibility, because of the uncertainty and irregularity of root and canal as well as the fact that no exact morphologies of roots and canals are available.

Studies aiming to remedy the defects of experimental methods, introduced a three-dimensional computerized numerical method to precisely evaluate and calculate the stress concentration and magnitude. FEA is a computerized method. It can solve complex problems by dividing complex structures (non-geometrical shape, e.g. tooth) into many small-interconnected simple structures (geometrical shape), which are called finite elements. It can directly display the location of stress concentration areas and the intensity of the stress. Given the above-mentioned advantages, FEA can be used to predict fracture patterns and fracture susceptibility. Variations of root shape and loads can be easily incorporated into the calculation to make the results more accurate and authentic. Combined with fracture strength test, FEA can provide comprehensive and convincing information about VRF for practitioners to take better preventive measurements.

7.2 FEA and fracture strength test in root canal therapy

As there is a high occurrence of VRF in endodontically treated teeth, endodontic procedures have been considered as a frequent cause of VRF.

One study, involving combined fracture strength testing and FEA to compare the preparation techniques of hand files and rotary Ni-Ti, demonstrated that the fracture load was almost identical, but the fracture pattern differed, and the FEA models correlated very well with the observed fracture pattern, demonstrating a reliable predictability for VRF(Sathorn *et al.* 2005a).

Another study by the same researchers found that dentin thickness, curvature of the external proximal root surface, canal size, and shape all interact in influencing fracture susceptibility and pattern of fracture (Sathorn *et al.* 2005b). The more dentin removed, the greater the fracture susceptibility. Canal preparation should be as conservative as practical, consistent with adequate cleaning and shaping. A smoothly rounded canal shape is favorable and can eliminate stress concentration sites, to reduce the fracture susceptibility. Studies have also revealed that canal wall curvature was a major influential factor in stress concentration and fracture pattern (Lertchirakarn *et al.* 2003a).

Besides having an application in endodontic procedures, FEA and fracture strength testing have also been used to evaluate different kinds of posts and crowns. For endodontically-treated teeth, it is pivotal to strengthen the fracture resistance. One study revealed that endodontically treated premolars whose coronal hard tissue were severely damaged, obtained higher fracture resistance with the computer-aided design/computer-aided manufacturing ceramic endocrown restoration compared with classical crown configuration (Lin *et al.* 2010). Another study showed that the combination of a fiber post and composite resin core with a full cast crown is most beneficial for the remaining tooth structure under the conditions of vertical and oblique loadings (Hayashi *et al.* 2006). The subsequent study of pulpless teeth with a combination of a fiber post and a composite resin core, compared to restorations using a metallic post, showed superior fracture resistance against both static and fatigue loadings, an approach therefore recommended in restoring pulpless teeth (Hayashi *et al.* 2008). However, a recent study has indicated that the endodontically-treated tooth without coronal tooth structure restored with titanium post showed higher fracture strength values as opposed to the composite post or no-post approach (Ozcan & Valandro 2009). It is reported that, in older patients, teeth receiving root canal treatment with posts are more prone to VRF, especially in those with low dentin thickness (Mireku *et al.* 2010). Consequently, clinicians should pay more attention to avoid VRF in older patients. A recent study using FEA confirmed the hypothesis that lack of an effective bonding between root and post increases the risk of VRF in upper premolars restored with endodontic posts (Santos *et al.* 2009), so an effective bonding can integrate the posts to the root canal. On the contrary, the conditions involving negative bonding will produce a torque force to form higher stress concentration areas, which will cause detrimental VRF to the root. A comparison of a fiber post core and a conventional cast post core system using conventional fracture strength test showed no obvious difference between the two post systems, but the finite elemental stress-analysis method revealed that stress was accumulated within the cast post core system. The stress transmitted to supportive structures and the tooth was low, because the post core system transferred the stress to the supportive structures and the tooth while stress accumulation within the post system was low (EskitascIoglu *et al.* 2002). This reminds the clinician to evaluate tooth conditions carefully before restoration, and to take special care with supporting tissues in their clinical activities. In endodontically-treated, single-rooted teeth with approximal cavities, fracture strength testing showed no advantageous fracture resistance in post groups (Heydecke *et al.* 2001). This conclusion may be different from others'. A study recommended the application of zirconia posts with ceramic cores as an alternative to cast posts and cores (Heydecke *et al.* 2002). The maxillary central incisors restored with a cast post and core demonstrated more vertical root fractures (Pontius & Hutter 2002). The preservation of both internal and external tooth structure is of utmost importance when restoring endodontically-treated teeth.

Experimental fracture strength tests were conducted and teeth had a significantly lower fracture resistance with stainless steel posts in place. The finite element model, from the point of stress distributions, confirmed the results. The failure of stainless steel posts was due to a worse mechanical performance and a high stress concentration because of the significant difference between the elastic modulus of the steel and the surrounding materials (Barjau-Escribano *et al.* 2006). This study again emphasized the importance of the similarity of the elastic modulus of the post, dentin and core, which determines the biomechanical performance of post systems. A study aiming to test the fracture strength in endodontically-treated premolars with a bonded restoration, full-coverage crown or onlay failed to discover significant difference (Steele & Johnson 1999).

Here, a problem we should note is that many studies are interested in single root teeth, rather than multi-root teeth. VRFs in molars are not infrequent, and happen even in non-treated, intact teeth, and often occur bilaterally. The high masticatory occlusal force is blamed for the occurrence of such unfavorable events. Because of the limitations in current research methods and the diversifications of root morphology, it is very difficult to simulate the real shape and pattern of the teeth, and the mechanical analysis is complex. Construction of a vivid multi-root model is an urgent task, and a formidable challenge, in order to provide theoretical supports for preventing VRF in molars.

8. The future challenge of FEA

Conventional technologies, the two-dimensional analysis of tooth and the strength tests, are unable to accurately determine subtle changes in teeth. In addition, direct assessment of the mechanical properties of teeth through mechanical experiment often brings errors and significant uncertainty to clinicians. This is because mechanical measurements are quite sensitive to friction between the sample and load patterns, and the result is largely dependent on the size and shape of the samples. Therefore, mechanical strength tests may not effectively detect small or even large changes of teeth. To overcome these technological shortcomings, FEA was introduced in measuring the mechanical properties of teeth. However, mastication forces are dynamic, and the magnitude is diverse at different times (Salis *et al.* 2006). From a clinical aspect, the results of monotonic analysis are questionable, not only is the monotonic load not representative of the clinical occlusal loads (Goto *et al.* 2005, Qing *et al.* 2007), but also the corresponding stress to dynamic and static loads are different. Static analysis ignores the stress-damping and stress-transmission effect of the soft tissues; thereby, an unexpected error is unavoidable.

Further, the root canal system is complex, which makes it difficult to completely know the root canal configuration and the stress distribution during endodontic treatment. It is well known that the accessory canals are impossible to clean mechanically. The high incidence of multiple canals and different canal types in premolars and molars, frequency of C-shaped canals in distal root of mandibular second molars, location of apical foramen, level of bifurcation, root canal ramifications, transverse anastomoses, apical deltas and any other variant anatomy are all factors preventing clinicians from successful treatment. FEA based on CT scanning can help to obtain a detailed picture of the complex root canal system, and establish the models to analyze the mechanical property and stress distribution before treatment commencement. This real-time simulation before any treatment undoubtedly facilitates the choice of the best therapeutic strategy. Doing so will protect the tooth structure and minimize the risk of improper operational approaches.

Recently, high-resolution microfocus computed tomography (CT) has been used successfully in endodontics, especially in measuring the diameters of the canal system. In previous studies (Barjau-Escribano *et al.* 2006, Steele & Johnson 1999), microfocus CT (micro-CT) produced valid root canal details in three dimensions, providing a visualized method to estimate canal preparation techniques. Micro-CT can directly compare different restoration conditions with the model of the unaltered tooth structure. Nowadays, with technological developments, advanced high-resolution CT will be widely applied in clinic. It will exactly detect the subtle variations and dynamic changes of each specific tooth. We can optimistically foresee that the exponential development of commercial dental CT-scanners, computer processing power, and friendly interface will make this approach even faster and more automated, offering the rapid model construction of patient-specific simulations of tooth structure.

Micro-CT also brings great challenges to FEA. Using micro-CT, a precise FEA model of a curved canal was established (Cheng *et al.* 2007). Furthermore, finite element (FE) models can be generated through the conversion of micro-images of the root canal system obtained from micro-CT to simulate real mechanical tests, which will largely eliminate the experimental errors and accurately provide an evaluation model of the root mechanical properties. It is true that small differences may exist between the reality and the finite element environment, but it is the best approach available to reveal the inaccessible stress distribution within the tooth-restoration complex, and the propensity that this numerical method has for increasing the power to imitate reality is irresistible. Therefore, FEA is a useful and crucial tool in endodontics.

Accurate dynamic FEA model is indispensable to investigate the stress concentrations in teeth under dynamic occlusal loads. To generate the model, the numerical analysis method of FEA is proposed to simulate the staged stress variation process. The complex time and special effect of dynamic occlusal loads poses a serious problem in analyzing the stress distribution. As for endodontically-treated teeth, using FEA and micro-CT will definitely help to create the best treatment strategy to keep the teeth in function as long as possible. In conclusion, to gain detailed information about root canal system, the method of three-dimensional modeling based on CT data is a promising approach. The use of FEA based on micro-CT images allows the changes in the microstructural and mechanical properties of teeth. This method has, to a large extent, helped endodontists to uncover the tooth strength properties and to develop effective therapeutic strategies, while the traditional method is far less useful. Moreover, developments in FEA will enable it to be even more practical and accurate.

9. Limitations of FEA

The use of FEA in dental research provides a qualitative and comparative studies method for varies stress problems. For the study of root canal therapy, FEA simulates and analyzes the stress within the root canal, on the root canal wall. This kind of study is superior to other techniques. FEA can take different and repeatable experiments on a single or a few typical subjects. It also brings in variables that cannot be approached by other means. In recent years, for the research on root canal therapy, FEA has most often dealt with: the stress and root fraction resistance of different preparation techniques; the stress analysis of obturation; and, the stress analysis of root fracture and vertical fracture.

Although FEA serves as a helpful and multifunctional technique, the limitations of FEA should not be ignored. As a computer solution, it does not necessarily reveal how the stresses are influenced by important variables such as materials properties and geometrical features. When FEA is used to simulate the tooth, the available model assumes the dentin is isotropic, linear elastic, and uniform with a tissue Young's modulus and Poisson's ratio. However, previous studies have shown that the hardness of dentin decreases from the outer surface to the dental pulp cavity, which makes the Poisson's ratio and Young's modulus not always the same within the dentin. It is also reported that dentin has its own anatomical shapes and structures. Thus, the Young's modulus varies according to the distance from the pulp. Simulating the true structure of the teeth to obtain an objective result is still a challenge for FEA.

In addition, the complicated geometry of root canals and uncertainties about their mechanical properties make it a necessity that calculated values must be corroborated by experimental measurements at certain points. These developmental defects within the teeth are often ignored in establishing an FEA model. However, the defects often potentially initiate the tooth fracture.

Moreover, most FEA experiments assume that the force distributed on the canal surface is uniform. Gutta-percha was simulated to behave like a perfect fluid, distributing the load around the canal wall equally and uniformly. In reality, this seldom happens. A pointed force is more likely the real situation of stress in the root canal under force of preparation or with condensation during obturation.

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Finite Element Analysis

Edited by David Moratal

ISBN 978-953-307-123-7

Hard cover, 688 pages

Publisher Sciyo

Published online 17, August, 2010

Published in print edition August, 2010

Finite element analysis is an engineering method for the numerical analysis of complex structures. This book provides a bird's eye view on this very broad matter through 27 original and innovative research studies exhibiting various investigation directions. Through its chapters the reader will have access to works related to Biomedical Engineering, Materials Engineering, Process Analysis and Civil Engineering. The text is addressed not only to researchers, but also to professional engineers, engineering lecturers and students seeking to gain a better understanding of where Finite Element Analysis stands today.