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STRESS DISTRIBUTION ON VARIOUS DEGREES OF CURVED ROOTS WITH DIFFERENT POST SYSTEMS BY FINITE ELEMENT ANALYSIS

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science Program in Endodontology
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ชญานี ชัชวานิชกุล : การกระจายความเค้นในรากฟันที่มีความโค้งหลายระดับ ร่วมกับการบูรณะด้วยเดือยระบบต่างๆ โดยใช้ระเบียบวิธีไฟไนต์เอลิเมนต์. (STRESS DISTRIBUTION ON VARIOUS DEGREES OF CURVED ROOTS WITH DIFFERENT POST SYSTEMS BY FINITE ELEMENT ANALYSIS) อ. ที่ปรึกษาวิทยานิพนธ์หลัก : รศ.ทพ.ดร. วีระ เลิศจิรการ, 87 หน้า.

จุดประสงค์ของการศึกษานี้คือเพื่อสำรวจและเปรียบเทียบการกระจายความเค้นในรากฟันที่มีความโค้งหลายระดับ ร่วมกับการบูรณะด้วยเดือยระบบต่างๆ โดยใช้ระเบียบวิธีไฟไนต์เอลิเมนต์ แบบจำลองฟันสามมิติทั้ง 16 แบบถูกสร้างขึ้นและปรับแต่งโดยใช้โปรแกรมคอมพิวเตอร์ โดยมีต้นแบบมาจากผิวด้านนอกของฟันกรามน้อยล่างซี่ที่สอง ร่วมกับการใส่แรงในสองทิศทาง พบว่า ระดับของความโค้งของรากฟันมีผลต่อรูปแบบการกระจายความเค้นเพียงเล็กน้อย เว้นแต่ถ้าแรงที่ลงนั้นมีทิศทางไปในทางเดียวกับความโค้งของรากฟัน ระดับความโค้งของรากฟันจะมีผลต่อทั้งในด้านรูปแบบการกระจายความเค้นและขนาดของความเค้น ในกรณีที่วัสดุบูรณะภายในรากฟันมีค่าโมดูลัสความยืดหยุ่นใกล้เคียงกับเนื้อฟัน ระดับความเค้นสูงสุดจะเกิดขึ้นบริเวณผิวด้านนอกของรากฟันเท่านั้น แต่เมื่อใดก็ตามถ้าค่าโมดูลัสความยืดหยุ่นของวัสดุบูรณะภายในรากฟันมีค่ามากกว่าเนื้อฟัน ระดับความเค้นสูงสุดจะไม่เพียงแต่เกิดขึ้นที่บริเวณรอยต่อระหว่างวัสดุบูรณะกับผนังคลองรากฟันเท่านั้น ยังเกิดบริเวณปลายเดือยโลหะด้วย ในสถานการณ์เช่นนี้มีโอกาสทำให้รากฟันหักได้ทั้งในแนวดิ่งและแนวนอน ดังนั้นในฟันกรามน้อยล่างที่มีความโค้งของรากและได้รับการรักษาคลองรากฟันโดยเปิดทางเข้าสู่โพรงฟันทางด้านบดเคี้ยวเพียงด้านเดียว อาจจะทำการบูรณะด้วยเรซินคอมโพสิตที่อุดลึกลงไปในคลองรากฟันระดับต้นเพียงอย่างเดียว แต่เมื่อใดที่มีการสูญเสียเนื้อฟันมากจนต้องการบูรณะด้วยเดือยแล้ว กลุ่มเดือยที่เป็นกลาสไฟเบอร์น่าจะเป็นวัสดุที่เหมาะสม โดยเฉพาะอย่างยิ่งในกรณีที่รากฟันมีความโค้งมาก

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CHAYANEE CHATVANITKUL : STRESS DISTRIBUTION ON VARIOUS DEGREES OF CURVED ROOTS WITH DIFFERENT POST SYSTEMS BY FINITE ELEMENT ANALYSIS. ADVISOR : ASSOC. PROF. VEERA LERTCHIRAKARN, D.D.S., Ph.D., 87 pp.

The aim of this study was to investigate and compare stress distribution in various degrees of curved roots with different post systems by finite element analysis (FEA). 16 3D-FEA models were created and adapted by using computer software based on external anatomy of mandibular second premolar. Two directions of load were applied. The results were expressed as the distribution of tensile and compressive stresses. The stress distribution showed that the degrees of root curvature in this study (15°, 30° and 45°) had a little effect on the stress distribution pattern except when the direction of force was the same as the root curvature. The degrees of root curvature affected both the stress distribution pattern and magnitude in the latter situation. When the modulus of elasticity of post and core materials was closed to the root dentin, the highest tensile stress concentration was found only on the external root surface. In contrast, when the modulus of elasticity of post and core materials was higher than those of root dentin, the highest tensile stress concentration was found both on the post-dentin interface and at post apex. This effect of metal post restoration increased when direction of force was the same as root curvature. Vertical or horizontal root fracture might occur in this condition. This study suggested that the suitable restoration in endodontically treated premolar with limited loss of tooth structure was resin composite that was filled in the coronal third of the root canal. However, when the post and core were indicated, the glass-fiber post and resin composite core were the materials of choice for restoration.

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CHAPTER I

INTRODUCTION

1.1 Background and rationale

The main goal of endodontic treatment is to keep the tooth with normal function as long as possible. This is possible because of advances in endodontics, which allow the tooth to be kept once it is devitalized, and advances in restorative dentistry, with its modern restoring techniques (Qualtrough *et al.*, 2003). However, the complicated root canal anatomy such as severe curved root may cause the complication of root canal treatment procedure.

The curved root canal may be one of the critical problems in endodontic therapy, especially during the root canal preparation. This can produce unwanted alterations in the canal shape. If these results in thin remaining root dentin, fracture is likely to happen. Stainless steel files and traditional preparation techniques often lead to transportation, ledge formation, and perforation (al-Omari *et al.*, 1992). However, improved instruments, especially NiTi-files, and techniques have decreased aberrations in canal and kept the original shape. With rotary NiTi preparation, canal shape is rounder and smoother than hand stainless steel file instrumentation (Bryant *et al.*, 1998). Therefore, the predictability of the pattern of fracture was reduced because of the lack of a highly localized tensile stress area (Sathorn *et al.*, 2005a).

Following root canal treatment, the tooth becomes weaker because a sound tooth structure has been removed to gain the good access and properly clean the root canal system. It is well known that the use of post to restore endodontically treated teeth does not increase the strength of the remaining tooth structure. Post only provides retention to the restoration (Caputo and Standlee, 1976; Christensen, 1998). In addition, post and core restorations are intended to transfer coronal forces to the root and supporting bone (Hirschfeld and Stern, 1972).

Many restorative alternatives are available because of the amount of the remaining tooth structure of an endodontically treated tooth, Cast post and core has been widely used to reestablish the tooth structure that is removed during endodontic treatment and destroyed by caries. In spite of its popularity, the cast post and core restoration has some disadvantages that may jeopardize long-term success. These disadvantages include tooth weakness related to the removal of root dentin to accommodate the necessary post length, lack of cement retention, corrosion risks, poor stress distribution leading to root fracture, necessity for two appointments to complete the procedure, and laboratory costs (Cohen and Hargreaves, 2006; Rosenstiel *et al.*, 2001).

Recently, dental researchers have attempted to incorporate fiber reinforcement technology into dental laboratory procedures and to add fibers to dental resins. Direct post and core restorations with prefabricated fiber-reinforced resin posts become popular because of their lower modulus of elasticity compared with metal post. Therefore, they can decrease the risk of root fracture (Boudrias *et al.*, 2001). These prefabricated posts, available in the market, can be categorized as active and passive.

Type of post may influence and cause horizontal or oblique root fracture. The recent study in anterior teeth found that tensile stresses occurred in three areas of root dentin: lingual bottom, labial side around post tip and the lingual top. These may cause root fracture in the future (Nakamura *et al.*, 2006). In addition, stress was found to increase dramatically and to concentrate in the small area of remaining dentin near the post apex when the level of alveolar bone crest decreased (Reinhardt *et al.*, 1983).

Root fracture usually occurs in the form of transverse root fracture and vertical root fracture. Both fractures have different etiologies and can lead to different treatment plan problems. If the tooth cannot restore, extraction is indicated at the present treatment plan.

A vertical root fracture (VRF) has a poor long-term prognosis. The fracture line usually extends from the root canal to the periodontium in buccolingual direction but in some cases may be incomplete fracture line (Cohen *et al.*, 2003; Lertchirakarn *et al.*, 2003a; Walton and Torabinejad, 2002). Diagnosis of vertical root fracture is not easy. The definitive diagnosis can perform when a fracture line is seen on the root surface during exploratory surgery. Once vertical root fracture is diagnosed, extraction of the involved single-rooted tooth or root amputation or hemisection of multiple roots in posterior teeth is indicated.

There are several etiologies of vertical root fracture. These have been suggested that excessive forces during lateral or vertical condensation leading to stress occurrence in the root canal wall during obturation (Meister *et al.*, 1980; Walton *et al.*, 1984), weakened tooth structure from oversized post preparation, excessive pressure during post cementation (Abou-Rass, 1983), and corrosion of posts or pins might be causes of vertical root fracture. In addition, there were reports that VRF was also occurred in nonendodontically treated teeth in Chinese population. These teeth showed severe attrition and fractures occurred almost in posterior teeth with minimal or no restoration (Chan *et al.*, 1998; Yang *et al.*, 1995).

The nature of existing forces in teeth and surrounding tissues has been a subject of investigation for a century. Stress analysis of dental structures is difficult because of the irregular shape of teeth. The surrounding tissues are the other difficult factors because of their non-homogeneous nature of the materials. Properties such as ultimate tensile and compressive strength and modulus of elasticity, vary greatly among the distinct material regions. The presence of prosthetic materials also introduces additional variations. Irregular geometry and non-homogeneity make the stress distribution analysis problem more complex (Davy *et al.*, 1981).

The Finite Element Method (FEM) has been widely used in engineering. In the last two decades, FEM has been proved to be extremely effective in dentistry as well (Lewgoy *et al.*, 2003). Finite element analysis is a numerical method to determine average results of the problems. The problem is divided in many subsections which are elements and nodes. Element is combined by nodes which positions are calculated the dependent variables. Finite element technique uses the computer to solve large numbers of equations which simulate the physical properties of the structure being analyzed. This approach can be applied to a wide variety of different structures having a large range of sizes and shapes. The finite element analysis model allows to study the details of stress magnitudes and distributions within structure. This system may aid in predicting fracture potential under given circumstances. When finite element modeling is compared with laboratory testing, it offers several advantages. The variables can be changes easily. Simulation can be performed without the need for human materials and it offers maximum standardization. In dental research, direct measurement of stress in root canal wall is impossible but the finite element analysis can solve this problem (Toksavul *et al.*, 2006).

Cheng and co-workers (2007) investigated stress distribution on curved canals of mandibular incisor at degree of root curvature about 38 degrees. The loading patterns were selected to simulate occlusive forces. The model was loaded in four directions (buccal, lingual, mesial, and distal) at 0, 30, 45 and 60 degrees to the long axis of the tooth. They found that stresses increased when the angle of the load increased, and loads in the distal and mesial directions induced more stresses in the target region than did loads in the buccal and lingual directions.

Up to date, there is no study investigates the effect of various degrees of curved roots of endodontically treated teeth to different post systems on stress distribution on root dentin.

1.2 Research questions

What does stress distribution pattern in various degrees of curved roots of endodontically treated teeth by restoration with different post systems?

1.3 Research objectives

To investigate and compare stress distribution pattern in various degrees of curved roots of endodontically treated teeth with different post systems.

1.4 Hypothesis

Null hypothesis H_0 : Stress distribution on various degrees of curved roots with different post systems of endodontically treated teeth is not different.

Alternative hypothesis H_A : Stress distribution on various degrees of curved roots with different post systems of endodontically treated teeth is different.

1.5 Keywords

Curved roots, stress distribution, FEA, post systems

1.6 Research design

Experimental research

1.7 Limitation of research

Finite element analysis is a purely numerical method. Validation of results is not always easy experimentally. In addition, tooth surface is irregular, so drawing it may not accurate as experiment.

1.8 Benefits

The ability to perform stress analysis on reconstructed teeth is of substantial importance in optimal restoration.

1.9 Ethical consideration

A human mandibular second premolar was extracted for orthodontic reason with patient's informed consent at the private clinic.

CHAPTER II

LITERATURE REVIEWS

The goals of endodontic and restorative dentistry are to retain natural tooth with maximum function and esthetics. Restoration of endodontically treated tooth replaces missing tooth structure, maintains function and esthetics, and protects against fracture and infection (Cohen and Hargreaves, 2006). Since root fracture has serious clinical implication in endodontically treated tooth, in order to avoid this complication, the method of restoration of endodontically treated tooth may be the important factor to prevent root fracture. In addition, in some roots of endodontically treated teeth are severe curved roots, which no any studies to suggest the relationship between degree of curved root and type of restoration in term of stress distribution. This literature review includes a consideration of degree of root curvature, changing in endodontically treated tooth, restoration of endodontically treated tooth, root fracture and stress analysis, especially finite element analysis.

I . Degree of root curvature

Schneider (1971) described the method to measure degree of root curvature from radiographic images in both a buccolingual plane and a mesiodistal plane. A line was drawn on the roentgenogram parallel to the long axis of the canal. A second line was drawn from the apical foramen to intersect with the first at the point where the canal began to leave the long axis of the tooth. From this study, the curved root was divided into three groups, based on degree of curvature, as follows: straight root (5 degrees or less); moderate (10 to 20 degrees); and severe (25 to 70 degrees) curved root (Schneider, 1971).

Fig. 1 Schematic of method to measure the degree of root curvature.

II . Differences in endodontically treated teeth

A. Destruction of tooth structure

The dimished amount of tooth structure from the combined effects of caries, dental procedures, and endodontic therapy significantly weakens nonvital teeth. Root canal procedures alone reduce tooth stiffness by only 5 percent, whereas tooth structure removal in a mesio-occluso-distal (MOD) preparation reduces tooth stiffness about 60 percent (Gutmann, 1992; Reeh *et al.*, 1989). In cases with significantly reduced remaining tooth structure normal functional forces may fracture undermined cusps, fracture the tooth off at the cemento-enamel junction (CEJ), or fracture the root.

B. Physical change in tooth structure

Changes in collagen cross-linking and dehydration of the dentin result in a 14 percent reduction in strength and toughness in endodontically treated molars. Maxillary teeth are stronger than mandibular teeth. Mandibular incisors are the weakest tooth. The *in vitro* study by Reeh and co-workers (1989) showed that endodontic procedure reduced tooth stiffness by only 5 percent. However, there was a study by Sedgley and Messer (1992) to compare biomechanical properties between endodontically treated teeth and contralateral vital pairs. The result indicated no difference in both groups. The authors concluded that teeth did not become more brittle following endodontic treatment.

C. Esthetic change in tooth structure

Biochemically altered dentin modifies light refraction through the tooth and correspondingly modifies its appearance. Inadequate cleaning and shaping can leave vital tissue in coronal pulpal horns, resulting in tooth darkening. Endodontic treatment and subsequent restoration of teeth in the esthetic zone require careful control of procedures and materials to retain a translucent and natural appearance (Cohen and Hargreaves, 2006).

Ⅲ. Restoration of endodontically treated teeth

Before restoration, endodontically treated teeth need to be assessed carefully for the following: good apical seal, no sensitivity to pressure, no exudates, no fistula, no apical sensitivity and no active inflammation (Johnson *et al.*, 1976).

A. Basic Principles in the Restoration of Endodontically Treated Teeth

The American Association of Endodontics (2004) supports the following guiding principles for restoration of endodontically treated teeth.

- Posterior teeth should receive cuspal coverage restorations. Bonded restorations provide only short-term strengthening of the teeth, according to recent studies.

- Anterior teeth with minimal loss of tooth structure can be restored conservatively with bonded restorations.

- Preservation of coronal and radicular tooth structure is desirable.

- The purpose of a post is to retain core buildup.
- A ferrule is highly desirable when a post is used. An adequate ferrule is considered a minimum of 2 mm of vertical height and 1mm of dentin thickness.

The treatment plan of the definitive restoration of endodontically treated teeth is strongly depended on the amount of the remaining tooth structure, the morphology of the tooth, its position in the dental arch, functional loading on the tooth and the esthetic requirements (Tait *et al.*, 2005). No restorative material can truly substitute for intact dentin (Cohen and Hargreaves, 2006). Extensive loss of tooth structure, such as a result of caries, fractures, or previous restorations significantly weakens the remaining tooth and increases risk for the following severe clinical problems (Al Wazzan, 2002; Tamse *et al.*, 1999);

- Root fracture,
- Devastating recurrent caries, coronal-apical leakage, and endodontic failure as a result of loss of the restorative seal,
- Dislodgment or loss of the final restoration as a result of dislodgment of the core,
- Periodontal injury from biologic width invasion during margin preparation.

Because of morphologic and functional differences between anterior teeth and posterior teeth, they are restored differently after endodontic therapy. This is mainly due to difference in loading considerations (Rosenstiel *et al.*, 2001). Restorations for endodontically treated teeth are designed to

- protect the remaining tooth structure from fracture,
- prevent reinfection of the root canal system, and
- replace the missing tooth structure (Cohen and Hargreaves, 2006)

The selection of individual components for the restoration depends on the location of the tooth, its functional requirements, and the amount of missing coronal or radicular tooth structure.

B. Principles in the use of a post

The post is a restorative material placed in the root of a structurally damaged tooth in which additional retention is needed for the core and coronal restoration. The purpose of the post is to be the retention of a core to support the coronal restoration. It also helps to protect the apical seal from bacterial contamination caused by coronal leakage (Goodacre and Spolnik, 1995). However posts do not strengthen teeth, and the preparation of a post space and the placement of a post can be weaken the root and may lead to root fracture (Guzy and Nicholls, 1979; Heydecke *et al.*, 2001). These studies also suggest that a post should be used only when there is insufficient remaining tooth structure to support the final restoration.

1. When to use a post

Many endodontically treated molars do not require a post because they have more tooth substance and a larger pulp chamber to retain a core material (Kane and Burgess, 1991). When sufficient tooth structure is present to retain the coronal restoration, the post is not needed. However, if occlusion is expected to be heavy or the tooth is planned to be a prosthetic abutment or visible crack, a post-and-core buildup should be carried out (Christensen, 1998). In addition, when a post is required as a result of extensive loss of tooth substance, it should be placed in the largest and straightest canal to avoid weakening the root during post space preparation and perforation in curved canals. Premolars have less tooth substance and smaller pulp chambers to retain core materials, so posts are required more often in premolars.

Some studies concluded that a post was not necessary in an endodontically treated anterior tooth with minimal loss of tooth structure (Guzy and Nicholls, 1979; Trope *et al.*, 1985). These teeth might be restored conservatively with a bonded restoration in the access cavity (Sorensen and Martinoff, 1984; Trope *et al.*, 1985). In addition, a study by Baratieri and co-workers (2000) demonstrated that the use of posts did not improve the fracture resistance of endodontically treated maxillary central incisors that was received direct composite veneers. The only conservative veneer preparation did not significantly reduce their fracture resistance.

2. Types of posts

There are two main categories of posts: custom-fabricated and prefabricated. Custom-fabricated gold cast post and core has been used for decades as a foundation of restoration to support the final restoration in endodontically treated teeth. The study by Bergman and co-workers (1989) reported a success rate of 90.6 percent using a cast gold post and core as a part of restoration at six years recall. Other base metal alloys have been used, but their hardness may be a major disadvantage in adjustment and may be a cause of root fracture.

Prefabricated post and core systems are classified according to their geometry (shape and configuration) and methods of retention. The methods of retention are designated as active or passive. Active posts engage the dentinal walls of the preparation on insertion, whereas passive posts do not engage the dentin but rely on cement for retention (Smith and Schuman, 1998; Terry *et al.*, 2001). The basic post shapes and surface configurations are tapered, serrated; tapered, smooth-sided; tapered, threaded; parallel, serrated; parallel, smooth-sided; and parallel, threaded. The active or threaded posts are more retentive than the passive posts. The active posts create high stress during placement and increase susceptibility to root fracture when occlusal forces are applied (Johnson *et al.*, 1976). Parallel-sided serrated posts are the most retentive of the prefabricated posts, and the tapered smooth-sided posts are the least retentive of all designs (Smith and Schuman, 1998). A photoelastic stress analysis of post designs led to the conclusion that cement-retained posts and parallel posts were the least stressful to the root, but they also were the least retentive posts (Rolf *et al.*, 1992).

3. Materials

The ideal post and core material should have physical properties such as modulus of elasticity, compressive strength and coefficient of thermal expansion that are similar to those of dentin (Cheung, 2005).

Stainless steel, titanium and titanium alloys, gold-plated brass, ceramic and fiber-reinforced polymers have been used as materials for prefabricated posts. Stainless steel has been used for a long time in prefabricated posts. However, it contains nickel, and nickel sensitivity is a concern, especially among female patients. Stainless steel and brass also have problems with corrosion.

Pure titanium has slightly lower physical properties, such as compressive and flexural strength, than other alloys, and it is the least corrosive and most biocompatible material. Furthermore, most titanium alloys used in posts have a radiographic density similar to that of gutta-percha. Therefore they are difficult to be detected by radiographs (Cheung, 2005).

Ceramic has good biocompatibility, high flexural strength and fracture toughness (Ichikawa *et al.*, 1992). It is esthetic, especially under all ceramic crowns. However, Hedlund and co-workers (2003) reported that ceramic post had poor bond strength with resin cement under fatigue test. This type of post is relatively new, and long-term clinical results are not yet available.

Another type of post is the fiber-reinforced polymer post. It is made of carbon or silica fibers surrounded by a matrix of polymer resin, which usually is an epoxy resin. The fibers are 7 to 10 micrometers in diameter and are available in a number of different configurations, including braided, woven and longitudinal. According to two *in vitro* studies (Newman *et al.*, 2003; Sirimai *et al.*, 1999) the physical strength of fiber-reinforced post is significantly weaker than that of cast metal posts and cores. The highly rigid metal post will transfer lateral forces without distortion to the less rigid dentin and lead to a higher chance of root fracture. On the other hand, the lower flexural modulus of fiber-reinforced post (1-4 x 10^6 psi), that is close to that of dentin (2 x10^6 psi) can decrease the incidence of root fracture (Sirimai *et al.*, 1999). In the mode of failure, teeth are more likely to be favourable when they are restored with fiber-reinforced posts. (Akkayan and Gulmez, 2002; Newman *et al.*, 2003). Fiber-reinforced posts are fabricated to bond with most resin cements and resin-based composite core materials. The successful bonding will minimize the wedging effect of the post within the root canal, so that it requires less dentin removal to accommodate a shorter and thinner post and led to lower susceptibility to tooth fracture. In addition, the shape (parallel versus tapered) of the fiber-reinforced post was reported that might be less significant in relation to its retention than for a metal post (Qualtrough *et al.*, 2003). Since the fiber-reinforced post is metal-free, it does not cause metal allergy or corrode. It offers good esthetics in easily visible areas of the mouth, especially under the all-ceramic crowns and bridges. Finally, the fiber-reinforced posts can be removed easily in case of an endodontic failure requiring re-treatment. Like the ceramic posts, the fiber-reinforced posts are relatively new, and data on their long-term clinical performance are not available yet.

4. Post designs

Caputo and Standlee (1976) categorized these different design features into three basic combinations:

- tapered, serrated or smooth-sided, cemented into a post space prepared with a matched-size post drill,
- parallel-sided, serrated or smooth-sided, cemented into matched cylindrical channels prepared by a post drill,
- parallel-sided, threaded and inserted into pretapped channels.

5. Post space preparation

The root canal should be enlarged only enough to enable the post to fit accurately and passively to ensure strength and retention (Rosenstiel *et al.*, 2001). Knowledge of root anatomy is important before attempting to prepare any canal space.

6. Post length

It was generally accepted that the apical 3 to 6 mm of gutta-percha must be preserved to maintain the apical seal (Zillich and Corcoran, 1984). Acceptable guidelines for determining the post length included the following:

- The post length should be equal to the clinical crown length (Goldrich, 1970).
- The post length should be equal to one-half to two-thirds of the length of the remaining root (Bartlett, 1968).
- The post should be equal to three quarters or more of the remaining root length, but leaving at least 3 mm of intact root canal filling from apex (Shillingburg *et al.*, 1970).
- The post should extend to one-half the length of the root that is supported by bone (Stern and Hirshfeld, 1973).

7. Post width

It is widely accepted that a post diameter makes little difference in the retention of a post. An increase in the post's width, on the other hand, will increase the risk of root fracture (Standlee *et al.*, 1978). In general, the post width should not exceed one-third of the root width at its narrowest dimension, and clinicians should bear in mind that most roots are not perfectly rounded (Morgano, 1996). A minimum of 1 mm of sound dentin should be maintained circumferentially, especially in the apical area where the root surface usually becomes narrower and functional stresses are concentrated (Caputo and Standlee, 1976).

8. Post cementation

Among the most commonly used dental cements, such as zinc phosphate, polycarboxylate, glass ionomer cement, resin-based composite and the hybrid of resin and ionomer cements, zinc phosphate cement has had the longest history of success. In addition, it is compatible with zinc oxide eugenol cement (ZOE), which is contained in most root canal sealers.

Resin-based composite cement increasingly becomes popular cement because of its potential to bond to dentin. Some authors have demonstrated concern regarding microleakage with thermocycling test of resin cements (Tjan *et al.*, 1991). Others, however, have shown to improve retention of posts (Chan *et al.*, 1993; Standlee and Caputo, 1992), decrease microleakage (Mannocci *et al.*, 2001) and higher fracture resistance of teeth (Mezzomo *et al.*, 2003).

C. The final restoration

Endodontically treated anterior teeth with minimal loss of tooth structure may be restored conservatively with a bonded restoration in the access cavity (Heydecke *et al.*, 2001; Sorensen and Martinoff, 1984; Trope *et al.*, 1985). Castings such as gold onlay, gold crowns, metal-ceramic crowns, and all-porcelain restorations with cuspal coverage are used routinely as standard and acceptable methods for restoration of posterior endodontically treated teeth.

In a three-year clinical study, Mannocci and colleagues (2002) concluded that the clinical success rates of endodontically treated premolars with limited loss of tooth structure restored with fiber-reinforced posts and direct composite were equivalent to full coverage with metal-ceramic crowns. Restoration with resin-based composite and acid etching of enamel and dentin could result in recovery of tooth stiffness up to 88 percent of unaltered teeth. This study suggested that the routine use of crowns on endodontically treated teeth might not be necessary if the marginal ridges were intact and most of the natural tooth substance was preserved.

Panitvisai and Messer (1995) studied the extent of cuspal flexure after endodontic and restorative procedures and found that cuspal deflection increased with extending cavity size in mandibular molars. The cuspal deflection was maximum value after endodontic access. The authors concluded that cuspal coverage is important so as to minimize the danger of marginal leakage and cuspal fracture in endodontically treated teeth.

In a 10-year retro-spective study of endodontically treated teeth by Aquilino and Caplan (2002), the endodontically treated teeth that did not receive crowns after obturation were lost six times more often than teeth that received crowns after obturation. The authors observed a strong association between crown placement and the survival of endodontically treated teeth. The authors suggested that it was safer to provide some kind of cuspal coverage in the final coronal restoration since most teeth that required endodontic treatment usually were severely damaged as a result of caries, fractures or both.

Ⅳ. Root fracture

Root fracture in permanent teeth usually occurs in the form of transverse root fracture and vertical root fracture. Both fractures have different etiologies. If the tooth cannot be restored, extraction is indicated.

A. **The transverse root fracture** usually occurs in maxillary anterior teeth of juveniles or after an injury from automobile or other accidents such as a fight or sporting whereas vertical root fracture usually occurs in both anterior and posterior teeth of adults after traumatic occlusion or iatrogenic procedure. The incidence of vertical root fracture however, is higher in posterior teeth. Transverse root fractures are fractures that involve the dentin, cementum, pulp, and periodontal ligament. They account for approximately 6 percent of all dental trauma and occur principally in the adult patient where the root is solidly supported in bone and periodontal membrane. In the younger patient the tooth is more likely to be avulsed (Feiglin, 1995).

B. Vertical root fracture (VRF) is a major clinical problem leading to extraction of single-rooted teeth or root amputation in molar (Pitts and Natkin, 1983). Many studies have shown that vertical root fracture occurs most commonly in the buccolingual plane (Cohen and Hargreaves, 2006; Geurtsen *et al.*, 2003; Lertchirakarn *et al.*, 2003a; Meister *et al.*, 1980; Morfis, 1990; Walton and Torabinejad, 2002). It may be initiated anywhere at or between the apex and the crown (Walton and Torabinejad, 2002) , and is responsible for 4.3 percent of endodontic failures (Vire, 1991). The long-term prognosis of VRF treatment is unfavourable because of complexities associated with material biocompatibility and poor capacity of the restorative materials to achieve radicular resistance to refracture (Trope and Rosenberg, 1992).

Predisposing factors to vertical root fracture have been suggested in many factors such as weakened tooth structure from oversized post preparation, excessive pressure during post cementation (Abou-Rass, 1983), stress in the root canal during obturation (Meister *et al.*, 1980; Walton *et al.*, 1984), and corrosion of posts or pins. The two most common causes are wedging forces of post placement and root canal obturation (Meister *et al.*, 1980). However, many variables are outside the control of the clinicians such as natural root morphology, canal shape and size, dentin thickness (Lertchirakarn *et al.*, 2003a; Sathorn *et al.*, 2005b), The other factors can be addressed during treatment to reduce fracture susceptibility including to final prepared canal shape, extent of canal enlargement and elimination of irregularities that serve as sites of stress concentration (Lertchirakarn *et al.*, 2003a; Sathorn *et al.*, 2005b).

There are many studies which attempt to analyze stress distribution in endodontically treated teeth. These studies have been performed using experimental methods such as strain-gauge measurements (Dang and Walton, 1989), photoelastic techniques (Martin and Fischer, 1990), and finite element analysis (FEA) (Ricks-Williamson *et al.*, 1995).

The stresses that may cause VRF are considered to be generated within the canal space, so the pattern of stress distribution on the root canal surface is likely to be critical in directing crack initiation and fracture propagation. The measurement of stresses on the surface of the root canal, however, is not technically feasible. As shown previously by Lertchirakarn and co-workers (2003) finite-element analysis (FEA) is a useful technique that can be used reliably in the analysis of stress distributions, with appropriate validation.

The excessive force during lateral compaction was reported to cause 84 percent of vertical root fractures with a sound at the time of filling (Meister *et al.*, 1980). However, vertical root fractures have been shown to occur with spreader loads as small as 1.5 kg (14.7 N). In addition, another investigation showed the mean load required to cause vertical root fracture was five to six times higher than the load used to fill a canal (Saw and Messer, 1995). It has been postulated that dentine may have sufficient elasticity to permit some separation of root segments without creating a complete fracture manifesting in small, incomplete fractures created at the time of fillings which may eventually become complete vertical root fractures later (Walton *et al.*, 1984). It is also possible that distortions are stored in dentine and remain quiescent over time. With additional stress applied through mastication or restoration, the latent fractures could occur as complete fractures at a later time. Dang and Walton (1989) suggested that it had not been established whether fractures occured at the time of filling or manifest themselves at a later time. At present, this fundamental question remains a point of contention because vertical root fracture is a complex issue that is difficult to study comprehensive.

V . Stress analysis

Stress analysis studies in dentistry have been conducted, using many methods as following :

A. Mechanical stress analysis: Extracted, restored, or natural teeth have been placed under an increasing load or force until either the tooth or restoration failed (fractured). Tensile forces were applied in several investigations (Newburg and Pameijer, 1976; Standlee *et al.*, 1978). However, loads applied in this manner may not duplicate the forces of masticatory function. Post systems have also been evaluated by loading at points and angles simulating tooth contact (Guzy and Nicholls, 1979; Perez Moll *et al.*, 1978). Fractures may occur at a variety of locations in these tests and did not give detailed information about stress distribution and magnitude prior to fracture.

B. Strain gauges: This technique has been used in models which simulate post and root (Derand, 1977). This method allows for complex mathematical measurements, but is limited by the number of gauges which can be placed and also by the accuracy of the model.

C. Photoelastic stress analysis: Photoelastic method provides a graphic demonstration of stress distributions by using a bi-refringent material through which light refraction is analyzed. The first work was studied by Noonan (1949) who used photoelastic models to study stress concentrations in amalgam restorations. The other studies have used photoelastic stress analysis to study a wide variety of restorative and other treatment procedures in dentistry. This method has also been used to test dentin stress from post installation (Standlee *et al.*, 1972; Standlee *et al.*, 1980) and as a result of functional loads (Henry, 1977). The major problem of photoelastic testing is that it is difficult to prepare complex models and to find model materials which exactly match the modulus of elasticity of human oral tissues.

D. Finite element analysis (FEA): FEA is an engineering technique which allows some of the problems inherent in the model systems to be approached in a different manner. Complex structures can be drawn and divided into many smaller segments, with specific physical properties. Stress distribution in response to a variety of loading conditions can be plotted with the aid of a computer. While finite element analysis has been shown to compare favorably with the photoelastic model, it has advantages that can provide information about the complete state of stress in a non-homogeneous material and allow for more detailed evaluation (Farah *et al.*, 1973).

The fundamental difficulty in attempting stress analysis of dental structures is the irregular shape of teeth. The compounding the tissue is the non-homogeneous nature of the materials in and around the tooth. Properties such as ultimate tensile strength, compressive strength and modulus of elasticity vary greatly among the distinct material regions. The presence of prosthetic materials also introduces additional variations. Irregular geometry and non-homogeneity make the stress analysis problem complex and minimize useful results from simple models of classical analysis (Davy *et al.*, 1981).

VI. Finite element analysis (Logan and Logan, 2002; Zienkiewicz *et al.*, 2005)

The finite element method is a numerical method for solving problems of engineering and mathematical physics. For problems involving complicated geometries, loadings, and material properties, it is generally not possible to obtain analytical mathematical solutions. Hence the study needs to rely on numerical methods, such as the finite element method. These numerical methods yield approximate values of the unknowns at discrete numbers of points in the continuum. This process of modeling a body by dividing it into an equivalent system of smaller bodies or units (finite elements) interconnected at points common to two or more elements (nodes) and/or boundary lines and/or surfaces is called discretization. In the finite element method, instead of solving the problem for the entire body in one operation, we formulate the equations for each finite element and combine them to obtain the solution of the whole body. The solution for structural problems typically refers to determining the displacements at each node and the stresses within each element making up the structure that is subjected to applied loads.

A. History

The development of the finite element method began in the 1940s in the field of structural engineering with the work by Hrennikoff in 1941 and McHenry in 1943, who used a lattice of line (1-D) elements (bars and beams) for the solution of stresses in continuous solids. The author, Richard Courant (1943) proposed setting up the solution of stresses in a various form. He introduced piecewise interpolation (or shape) functions over triangular subregions making up the whole region as a method to obtain approximate numerical solutions. In 1954, Argyris and Kelsey developed matrix structural analysis methods using energy principles. The first treatment of two-dimensional elements was introduced by Turner and co-workers in 1956. The extension of the finite element method to three-dimensional problem with development of a tetrahedral stiffness matrix was done by Martin in 1961, by Gallagher and colleague in 1962, and by Melosh in 1963. Additional three-dimensional elements were studied by Argyris in 1964. In 1976 Belytschko considered problems associated with large displacement nonlinear dynamic behavior and improved numerical techniques for solving the resulting systems of equations.

From the engineering side, the finite element analysis originated as the displacement method of the matrix structural analysis, which emerged over the course of several decades mainly in British aerospace research as a variant suitable for computers by late 1950s. The key concepts of stiffness matrix and element assembly existed essentially in the form used today and NASA issued request for proposals for the development of the finite element software NASTRAN in 1965.

B. Introduction to matrix notation

Matrix methods are a necessary tool used in the finite element method for purpose simplifying the formulation of the element stiffness equation, for purposes of long-hand solutions of various problems, and most important for use in programming methods for high-speed electronic digital computers. Hence matrix notation represents a simple and easy-to-use notation for writing and solving sets of simultaneous algebraic equations. A matrix is a rectangular array of quantities arranged in rows and columns that is often used as an aid in expressing and solving a system of algebraic equations. The global nodal forces F and the global nodal displacements d are related through use of the global stiffness matrix K by

$$\boxed{F=Kd}$$

It is the basic equation formulated in the stiffness or displacement method of analysis. The finite element method involves modeling the structure using small interconnected elements called finite elements. A displacement function is associated with each finite element. Every interconnected element is linked, directly or indirectly, to every other element through common interfaces, including nodes and/or boundary lines and/or surfaces. By using known stress/strain properties for the material making up the structure, one can determine the behavior of a given node in terms of the properties of every other element in the structure. The total set of equations describing the behavior of each node results in a series of algebraic equations best expressed in matrix notation.

C. Application and Advantage

Finite element method can be used to analyze both structural and nonstructural problems. Typical structural areas include

1. Stress analysis and stress concentration problems typically associated with holes, fillets, or other changes in geometry in a body.
2. Buckling
3. Vibration analysis

Advantages of the finite element method

1. model irregularly shaped bodies quite easily
2. handle general load conditions without difficulty
3. model bodies can compose of several different materials because the element equations are evaluated individually
4. handle unlimited numbers and kinds of boundary conditions
5. vary the size of the elements to make it possible to use small elements where necessary
6. alter the finite element model relatively easily and cheaply

7. include dynamic effects
8. handle nonlinear behavior existing with large deformations and nonlinear materials

D. Finite element analysis

In general, there are three phases in any computer-aided engineering task:

1. Pre-processing – defining the finite element model and environmental factors to be applied to it
2. Analysis solver – solution of finite element model
3. Post-processing of results using visualization tools

1. Pre-processing

The first step in using FEA, pre-processing, is constructing a finite element model of the structure to be analyzed. The input of a topological description of the structure's geometric features is required in most FEA packages. This can be in either 1D, 2D, or 3D form, modeled by line, shape, or surface representation, respectively, although nowadays 3D models are predominantly used. The primary objective of the model is to realistically replicate the important parameters and features of the real model. The simplest mechanism to achieve modeling similarity in structural analysis is to utilize pre-existing digital blueprints, design files, CAD models, and/or data by importing that into an FEA environment.

Once the finite element geometric model has been created, a meshing procedure is used to define and break up the model into small elements. In general, a finite element model is defined by a mesh network, which is made up of the geometric arrangement of elements and nodes. Nodes represent points at which features such as displacements are calculated. FEA packages use node numbers to serve as an identification tool in viewing solutions in structures such as deflections. Elements are bounded by sets of nodes, and define localized mass and stiffness properties of the model. Elements are also defined by mesh numbers, which allow references to be made to corresponding deflections or stresses at specific model locations.

2. Analysis (computation of solution)

The next stage of the FEA process is analysis. The FEA conducts a series of computational procedures involving applied forces, and the properties of the elements which produce a model solution. Such a structural analysis allows the determination of effects such as deformations, strains, and stresses which are caused by applied structural loads such as force, pressure and gravity.

3. Post-processing (visualization)

These results can then be studied using visualization tools within the FEA environment to view and to fully identify implications of the analysis. Numerical and graphical tools allow the precise location of data such as stresses and deflections to be identified.

E. Finite element software

- Abaqus
- ALGOR
- ANSYS
- Calculix
- COMSOL Multiphysics
- DUNE
- Femap
- LS-DYNA

- MARC
- NASTRAN
- STRAND7

F. Current FEA trends in Dentistry

Finite element analysis is a very powerful and popular numerical method in stress analysis. It has been applied in dental mechanics for nearly three decades. The usefulness of the finite element method for studying problems in dentistry has long been established by Hood, Farah and Craig (Hood *et al.*, 1975), Farah, Dennison and Powers (Farah *et al.*, 1977) and Peters (1981). Gupta and colleague (1973) used a three-dimensional finite element model of mandible to evaluate stresses and displacements within the model, and compared these to stresses and displacements on actual mandibular specimens using holographic interferometry. Agreement was obtained within one order of magnitude in a comparison of these two techniques.

Arola and co-workers (2001) stated that the FEM should be a fundamental in the studies that investigated stresses generated in restored teeth. The stress distribution in the cervical, middle and apical areas of the root is extremely important, therefore it is important that the shape and type of the material should be less traumatic to the dental root during masticatory function.

Many efforts have been made to analyze the stresses in the human tooth, surrounding structures, and artificial tooth replacements and supports. A survey of the literature in this area reveals a multitude of applications for such research. A few of these are listed below :

- The shape and design of restorations, crowns dental implants, dowels, retention pins, partial dentures, and bridges (Holmes *et al.*, 1996; Standlee *et al.*, 1978)

- The interactions of bone, periodontal ligament and tooth (Naumann *et al.*, 2006; Takahashi *et al.*, 1980)
- The study of thermal and setting effects and resulting residual stresses in restorations and crowns (Yang *et al.*, 2001)
- The physical, biochemical, and biologic effects of chewing forces e.g., the effects that occlusal forces have on bone growth and caries development (Neumann and Disalvo, 1957)
- The effects of orthodontic appliances (Oyama *et al.*, 2007).
- The factors that influence the stress distribution in root canal wall and cause VRF (Lertchirakarn *et al.*, 2003a)
- Recently, the stress distribution on curved canals of mandibular incisor at degree of root curvature about 38 degrees was investigated. The loading patterns were selected to simulate occlusive forces. They found that stresses increased when the angle of the load rose, and loads in the distal and mesial directions induced more stresses in the target region than did loads in the buccal and lingual directions (Cheng *et al.*, 2007).

The problem of tooth stresses is very complicated because of the non-homogeneous character of tooth material and the irregularity of tooth contours. The tooth structure is composed of several different materials such as enamel, dentin, pulp, cementum, periodontal ligament, and bone. Each of these has widely varying properties. The problem is further complicated by large variations (both in magnitude and direction) of chewing forces. Conventional methods of stress analysis in which exact solutions may be obtained are not useful in problems as complicated as these. The non-homogeneities and discontinuities, as well as the three-dimensional nature of the tooth and the forces acting on it, preclude the derivation of a description of the structure using differential equations. However, computer techniques, such as finite element analysis, can help to solve theses problems of this nature (Rubin *et al.*, 1983).

The three-dimensional analysis is more efficient and accurate than existing two-dimensional analyses because of the following reasons:

1. The human tooth is neither planar nor symmetric. It is also highly irregular in shape.
2. The loading on the tooth is neither in a state of plane stress nor is it symmetric. Such assumptions would be expected to produce considerable errors in calculations of the stress distribution within the tooth.
3. The distribution of the various materials of which the tooth is composed (enamel, dentin, pulp, etc.) does not lend itself to two-dimensional modeling.

Direct measurement of stresses and strains in the wall of the root canal is impossible. The distribution of stresses is likely to be complex and the internal canal wall is inaccessible for the placement of measuring devices such as strain gauges. The use of strain gauges has been limited to placement at selected sites on the root surface, which may not reflect strain patterns within dentin (Lertchirakarn *et al.*, 2003b). Previous studies have examined stress distribution in roots using FEA (Lertchirakarn *et al.*, 2003a; Ricks-Williamson *et al.*, 1995; Yaman *et al.*, 1995). However, FEA is based on many limiting assumptions. Validation of results is not always easy experimentally.

CHAPTER III

MATERIALS AND METHODS

Creation of tooth model

Stress distributions in the remaining tooth structure were investigated under the condition of various degrees of curved roots with different post systems in mandibular left second premolar using three-dimensional finite element analysis software program (MSC Patran 2007 r1a and MSC Marc 2007r1, MSC.Software Corporation, Santa Ana, CA, USA). The original tooth model was created by digitizing the external surface of an extracted human mandibular second premolar with a straight root using a structured light optical scanner (GOM Atos II, GOM mbH, Braunschweig, Germany) in combination with computer software (Raindrop geomagic studio 10, Geomagic, Inc., Triangle Park, NC, USA).

Fig. 2 Morphology of original tooth model created by digitizing extracted human mandibular second premolar tooth.

The original tooth model was adapted to reconstruct the other tooth models that had various degrees of curved roots as described by Schneider (1971) using the computer software (Raindrop geomagic studio 10). The direction of the curved root apex was forward to distal direction in every model. The other software (Unigraphic NX5, UGS Corp., Plano, Texas, USA) was used to create internal interface (Enamel-dentin-pulp junction) based on regular dental anatomy of mandibular second premolar tooth (Ash and Wheeler, 1993). A 200 µm thickness of periodontal ligament (PDL) layer and a normal surrounding cancellous bone volume were attached to support the root. Cementum was not separately created and was considered to be corporated in the root dentin. Subsequently, the standard access opening was made in the crown and the root canal preparation was created 0.04 taper with a final apical preparation of 0.35 mm at the point of constriction (Rundquist and Versluis, 2006). All the canal preparations were circular as commonly used nickel-titanium rotary files.

The sixteen models were created with one control groups and four experimental groups with different degrees of root curvature (15°, 30°, and 45°) and different methods of restoration. All the models comprised of normal bone height and normal PDL space.

Tooth modeling

Group I: This group consisted of the first to the fourth models which had curved roots at less than 5 (straight root), 15, 30, and 45 degrees, respectively. The root canals in these models were not treated. This group was served as a control.

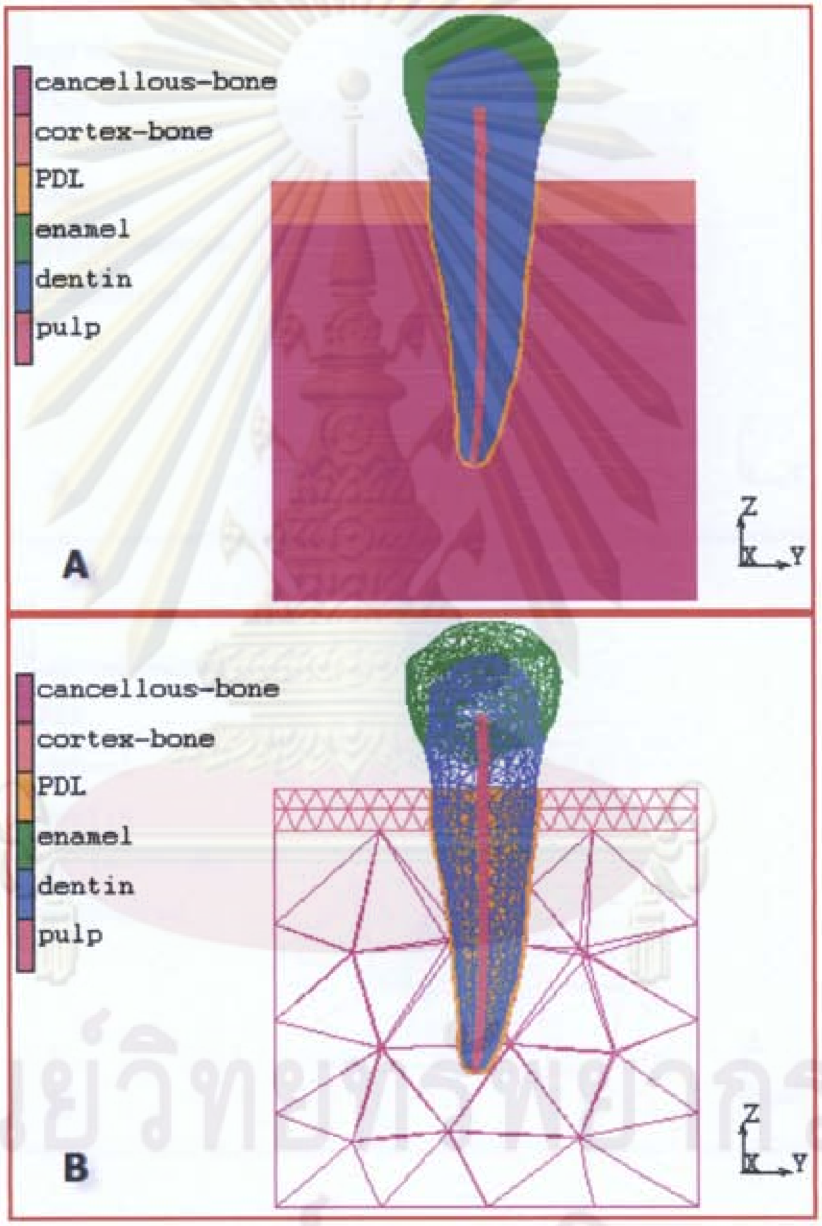

Fig. 3 A, Bucco-lingual view of the straight root (≤ 5°) mandibular second molar (the first model in group I).

B, the same model as (A) but showed in mesh model.

Group II: This group consisted of the fifth to the seventh models which had curved roots at 15, 30, and 45 degrees, respectively. The root canals in this group were prepared and restored with resin composite without crowns.

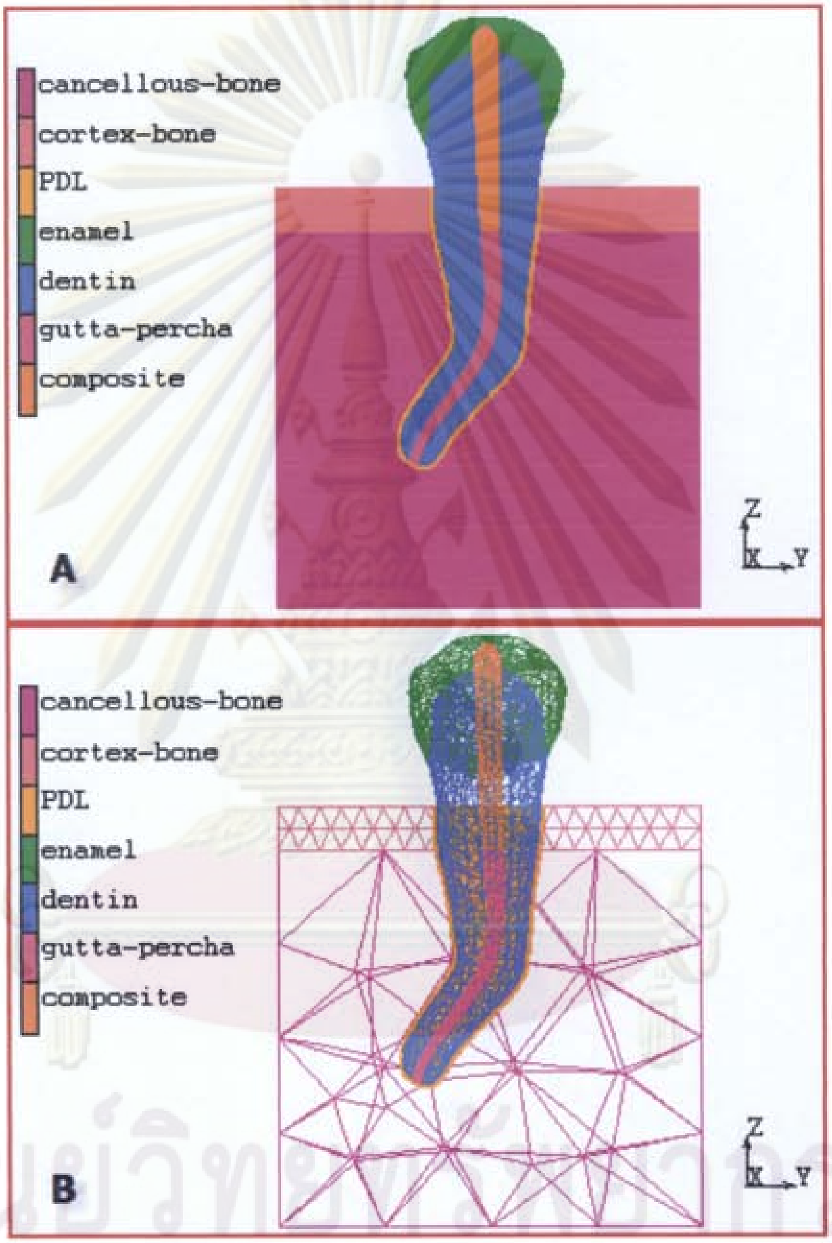

Fig. 4 A, Bucco-lingual view of the sixth model (30° curved root in group II which restored with resin composite without crown).

B, the mesh view of the sixth model.

Group III: This group consisted of the eighth to the tenth models which had curved roots at 15, 30, and 45 degrees, respectively. The root canals were prepared and restored with resin composite core and porcelain fused to metal crowns.

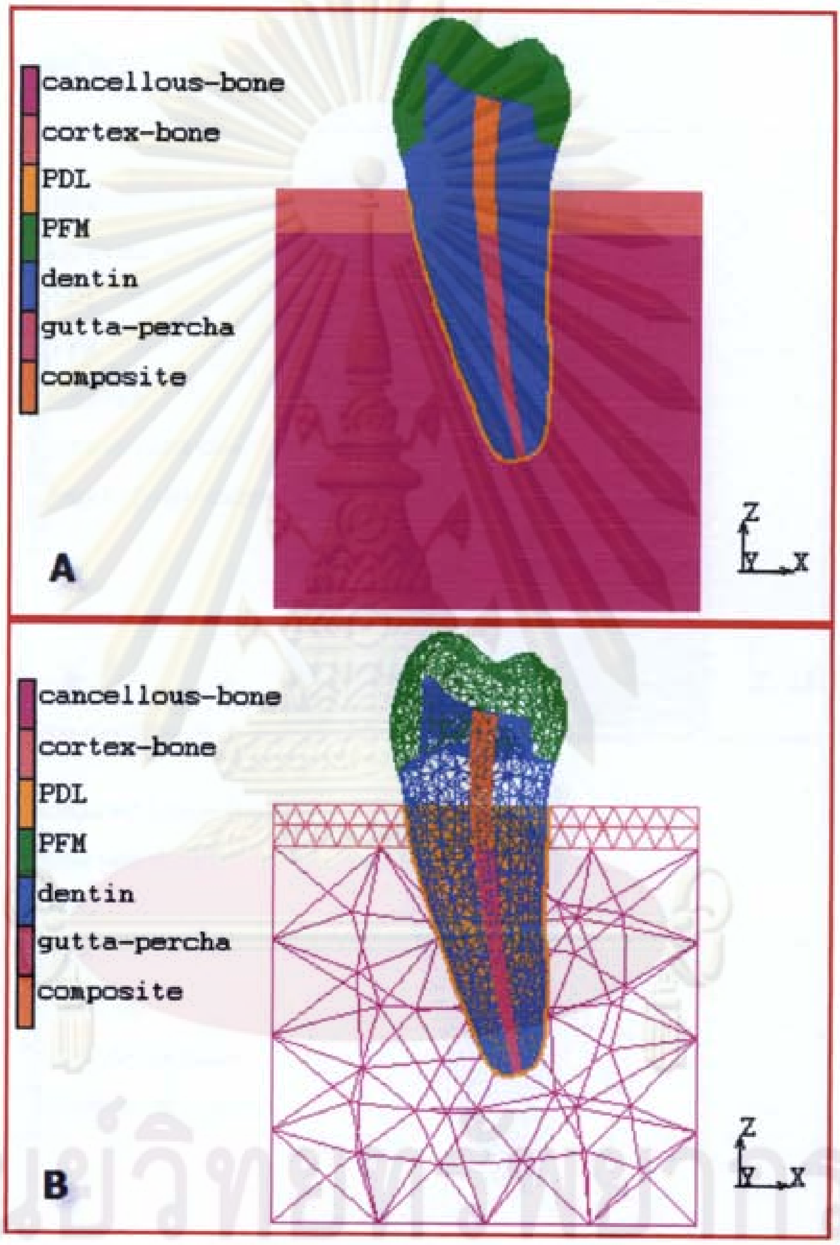

Fig. 5 A, Mesio-distal view of the tenth model (45°) in group III which restored with resin composite core and porcelain fused to metal crown (PFM).

B, the mesh view of the tenth model.

Group IV: This group consisted of the eleventh to the thirteenth models which had curved roots at 15, 30, and 45 degrees, respectively. The root canals were prepared and restored with nickel-chromium (Ni-Cr) alloy cast post and core by considering the morphological characteristics of a tooth, then porcelain fused to metal crowns were applied.

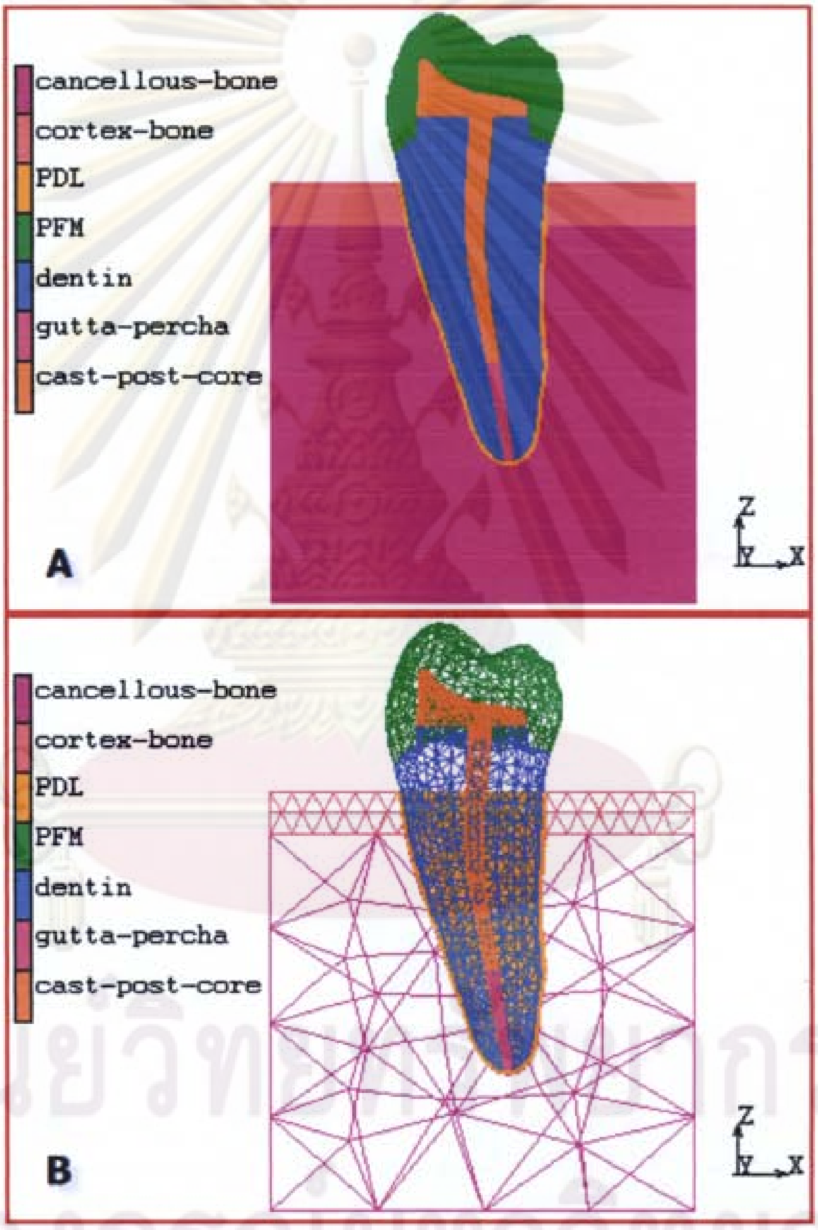

Fig. 6 A, Mesio-distal view of the eleventh model (15°) in group IV which restored with cast post and core and porcelain fused to metal crown (PFM).

B, the mesh view of the eleventh model.

Group V: This group consisted of the fourteenth to the sixteenth models which had curved roots at 15, 30, and 45 degrees, respectively. The root canals were prepared and restored with prefabricated cylindrical post (glass fiber) with composite core and porcelain fused to metal crowns.

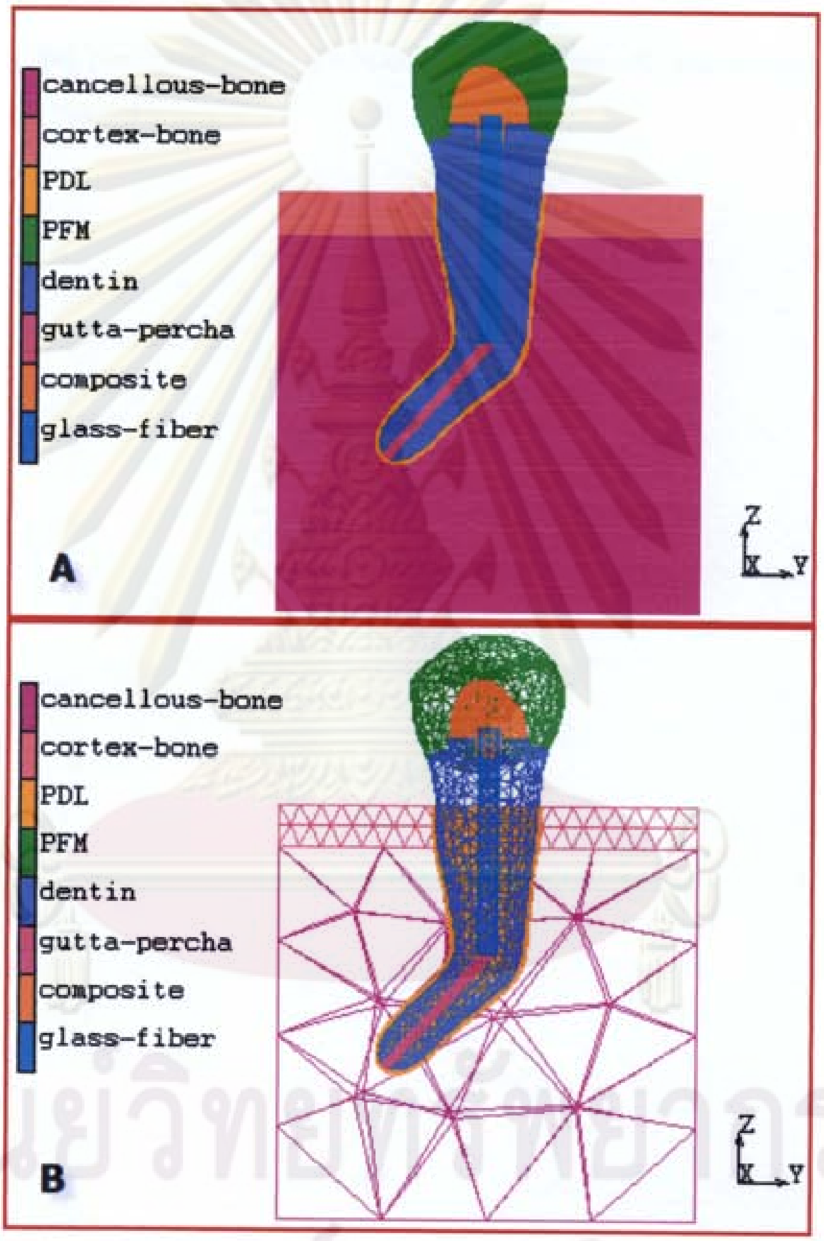

Fig. 7 A, Bucco-lingual view of the sixteenth model (45°) in group V which restored with cylindrical glass-fiber post with resin composite core and porcelain fused to metal crown (PFM).

B, the mesh view of the sixteenth model.

The resin composites were simulated in the root canal in 4-mm depth under the CEJ in the models that restored with resin composite. All the post lengths were assumed to apply at two-thirds of the root lengths. The remaining 4 to 5 mm of the root canal spaces near the apex were assumed to be filled with gutta-percha. In all of the applications, the porcelain crown thickness was 1.5 mm. All the model details were summarized in Table I.

Group	Model	Angle of curvature	Elements	Nodes
group I: Control; Without root canal preparation and restoration	1	≤ 5°	48,421	76,994
	2	15°	40,852	66,136
	3	30°	44,321	71,093
	4	45°	38,975	63,891
group II: restored with resin composite without crown	5	15°	34,659	57,683
	6	30°	38,558	63,470
	7	45°	35,405	59,147
group III: restored with resin composite core and PFM crown	8	15°	41,109	66,274
	9	30°	41,948	67,696
	10	45°	40,778	66,321
group IV: restored with cast post and core and PFM crown	11	15°	45,470	72,609
	12	30°	47,638	76,281
	13	45°	46,399	74,858
group V: restored with glass-fiber post and PFM crown	14	15°	45,250	73,368
	15	30°	45,340	73,189
	16	45°	46,702	75,941

Table I Summarized of all groups and models details with the numbers of nodes and elements.

Each model was structurally meshed by solid elements defined by nodes having six degrees of freedom in tetrahedral bodies (MSC Patran 2007 r1a). The amount of nodes and elements in each model were shown in table I. Isotropic properties were applied to all materials in the models, except for that of the glass fiber post. The cementum layer was too thin and its modulus of elasticity was close to that of dentin (Ho *et al.*, 1994), so cementum was applied as a dentin properties. The applied material properties were summarized in Table II.

Material	Modulus of Elasticity (GPa)	Poisson's ratio	References
Enamel	84.1	0.33	(Farah *et al.*, 1989)
Dentin	18.6	0.31	(Peyton *et al.*, 1952)
Pulp	0.00207	0.45	(Rubin *et al.*, 1983)
PDL	0.0689	0.45	(Weinstein *et al.*, 1980)
Cortical bone	13.7	0.3	(Carter and Hayes, 1977)
Cancellous bone	1.37	0.3	(Carter and Hayes, 1977)
Gutta-percha	0.292	0.45	(Friedman *et al.*, 1975)
Ni-Cr alloy	172	0.32	(Kase and Tesk., 1984)
Porcelain (Ceramco)	86.2	0.19	(Farah and Craig, 1975)
Composite resin	16.6	0.24	(Willems *et al.*, 1992)
Glass fiber	40(11)*	0.26 (.32, .07)*	(Pegoretti *et al.*, 2002)

* transverse properties

Table II The mechanical properties of materials used in the study

The following assumption had been made in terms of the properties of materials concerned in this study as following:

1. The tooth under consideration was composed of enamel, dentin, pulp, gutta-percha, and restorative materials.
2. Each model was supported by periodontal ligament, cortical and cancellous bone with each assigned the appropriate physical constants.
3. The materials were assumed to be homogeneous, isotropic and linearly elastic.
4. As boundary conditions, displacement of all nodes on the lateral surface and base of the cylinder that represent the bone were constrained.
5. All bonds at interface between dentin and post materials were assumed to be perfect bonds.

Load

Load case I

Force, 50 N, was applied in the buccolingual plane to the triangular ridge of the buccal cusp at an angle of 60 degrees with the vertical axis (Rundquist and Versluis, 2006). This loading position was imitated to occlusal force as described by Rundquist and Versluis, 2006 (Fig. 8).

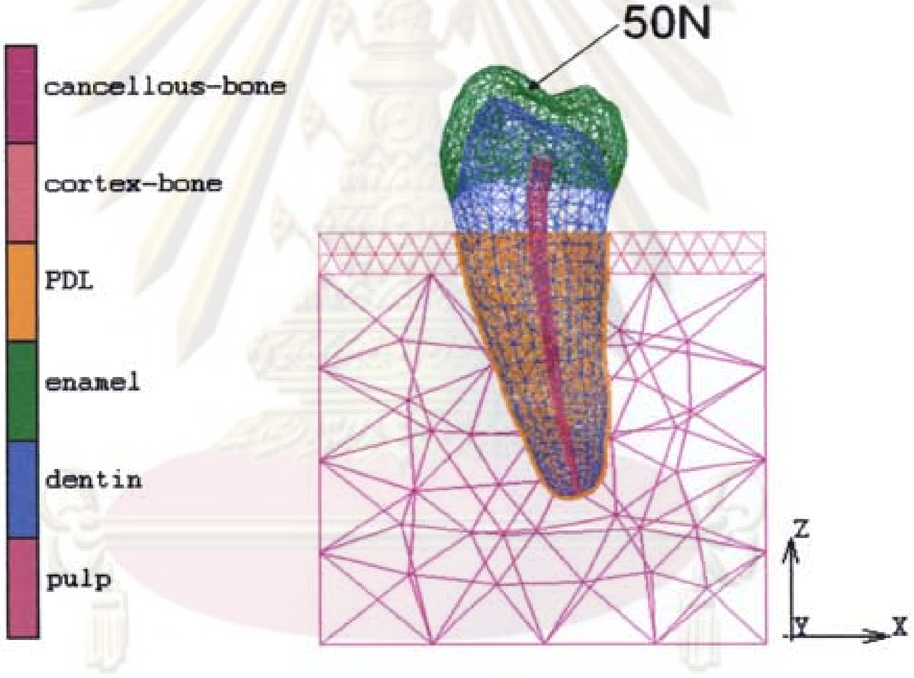

Fig. 8 Mesio-distal view of the straight root model was shown to demonstrate the location and direction of applied load case I

Load case II

Since the results from Cheng and co-workers' study (2007) demonstrated that the direction of applied force in relationship with direction of root curvature had the effects of stress distribution, the load case II was additionally applied in this study.

Force, 50 N, was applied in the mesiodistal plane to the triangular ridge of buccal cusp at an angle of 60 degrees with the vertical axis in the same direction of the root curvature. This load was represented in the tooth that having buccolingual curved root or tooth rotation. These could make the direction of force went through the same direction of curved roots (Fig. 9).

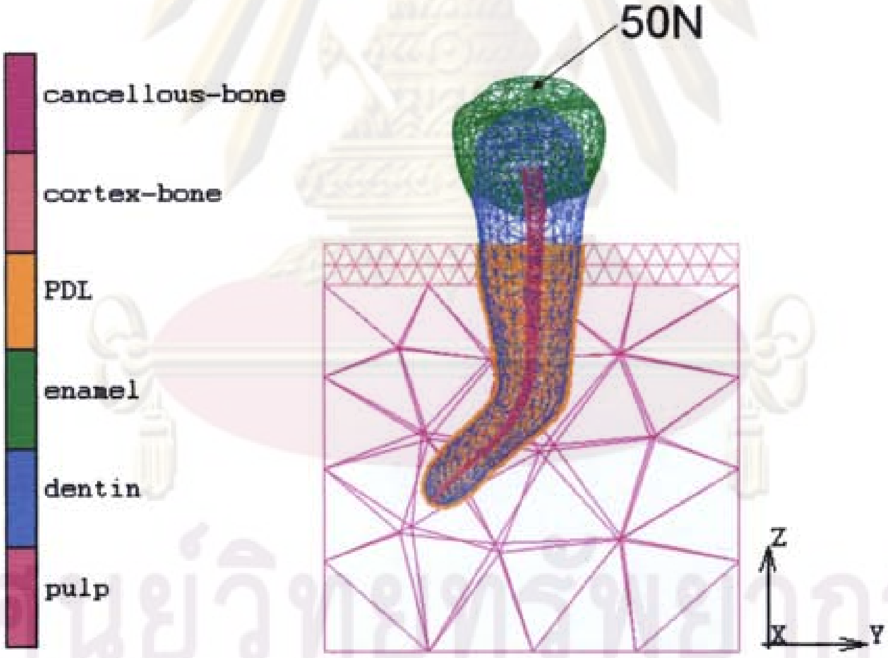

Fig. 9 Bucco-lingual view of the fourth model (45° curved root) was shown to demonstrate the location and direction of applied load case II, the same direction of the curved root.

Analysis

The development of stresses with the applied loads was analysed using finite element analysis software MSC-Marc 2007 r1 (MSC Marc 2007 r1). A linear static structural analysis was performed to calculate the FEA model. The results were presented in the mesio-distal cutting plane to demonstrate the stress concentration areas in the dentin and restorative materials. The stress contour bands were represented stress variation graphic of compressive and tensile stresses. This study demonstrated and compared stress concentration in each model. From the results we could predict pattern of root fracture and could also choose optimal restorations in various degrees of curved roots.

CHAPTER IV

RESULTS

Because of the basic concept of FEA, the result of the method is only an approximate solution. Results, thus, in this study are presented in qualitative rather than quantitative terms. The magnitudes and location of stresses are compared. Stress distribution was shown graphic colors of cutting plane in mesio-distal direction of the models. The areas with the same color were subjected to same range of stresses. The results were presented in stress contour bands which represented stress variation graphic of compressive and tensile stresses in tooth structures and restorative materials. The tensile stresses were shown in positive values and compressive stresses were shown in negative values.

The Von Mises stress is not presented in this study because this stress is the best criteria for failure of ductile fracture, while dentin fracture has been suggested for evaluation of fracture in brittle fracture (Lertchirakarn *et al*., 2003a). In addition, Von Mises stress is the total (vector) stress which combines compressive and tensile stress. Thus, Von Mises stress is not suitable to be the failure criteria for dentin because dentin normally fails in tensile stress rather than compressive or Von Mises stress.

The results from load case I models of group I, II, III and V were shown in Fig. 10, 11, 12 and 14, respectively. The results from these groups demonstrated that the highest tensile stresses concentrated only on the distal side (concave side) of the external root surface in the straight part above the curvature or at the coronal and middle third of the external root surface. The compressive stresses concentrated on the opposite side or the mesial side (convex side) of the external root surface. Stress distribution patterns and magnitudes of group I, II, III and V were not different. However, it was interesting that the area of highest stress concentration was larger while the degree of root curvature increased in each group.

In the case of group IV of load case I models as shown in Fig. 13, the stress distribution pattern and magnitude were different from the others. The results in this group showed the tensile stresses in both external root surface and internal root canal wall. At the external root surface, the tensile stresses were the same as other groups both in locations and magnitudes. However, the magnitude of the tensile stress concentration in the root canal wall or on the post-dentin interface was also higher than in the other groups. In addition, as the degrees of curved roots were increased, more stresses concentrated on the post-dentin interface. Interestingly, the high tensile stress concentration was also found at the apical end of the casting post. The compressive stresses concentrated on the mesial side (or the convex side) of the external root surfaces in the same manner as other groups. The stress distribution in load case I of each group was shown in Fig. 10-14.

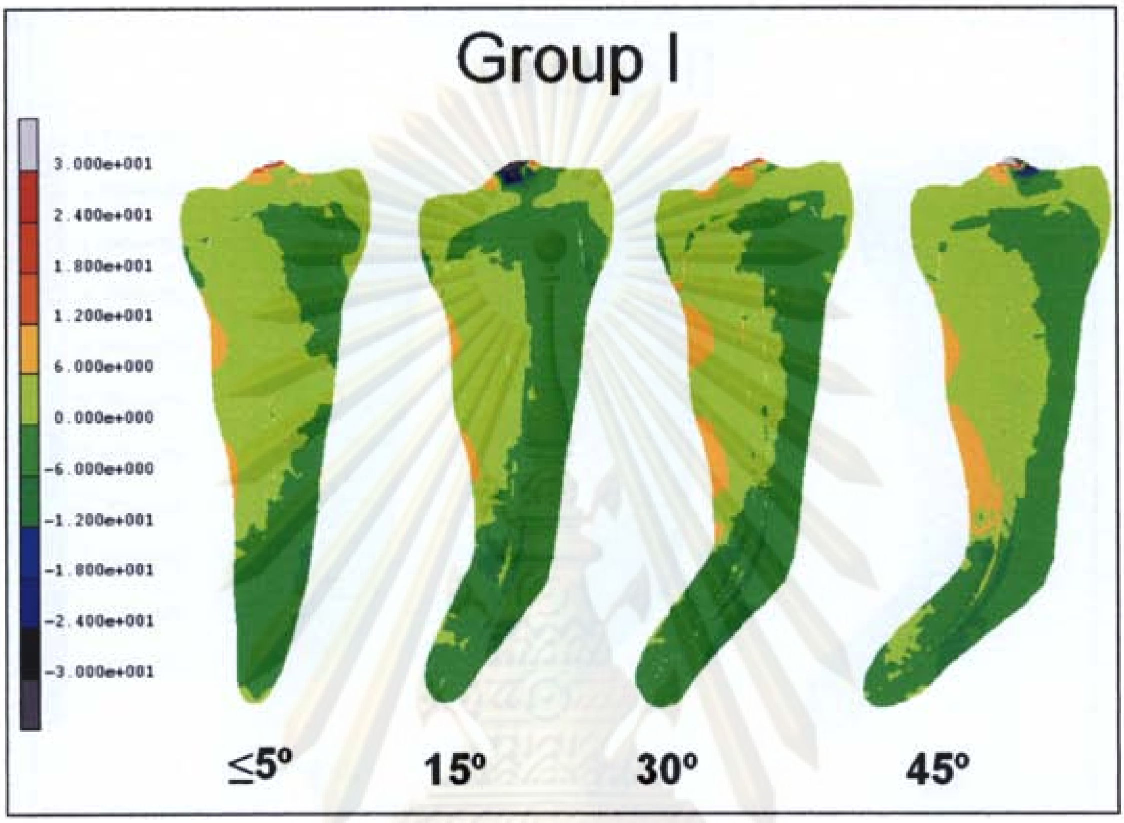

Fig. 10. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case I in mesio-distal plane of group I (control, non-RCT tooth) which was composed of the first to the fourth model that had curved roots at less than 5°, 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

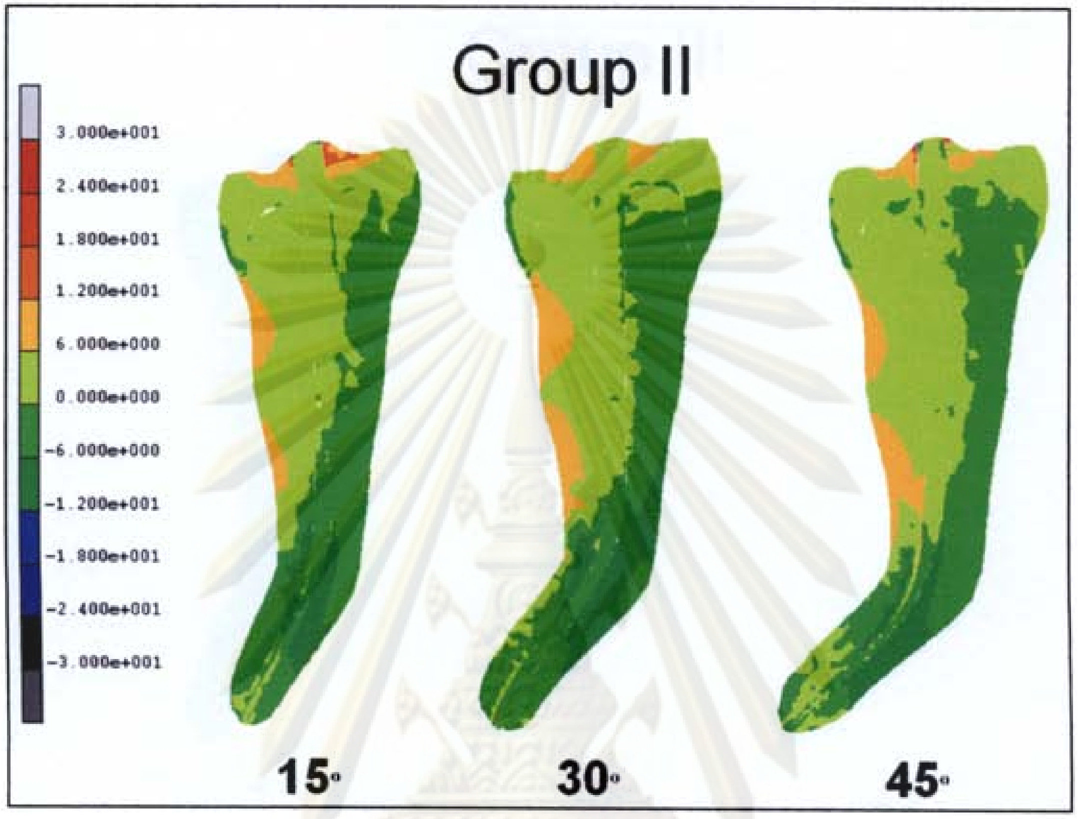

Fig. 11. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case I in mesio-distal plane of group II (prepared root canal and restored with resin composite) which was composed of the fifth to the seventh model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

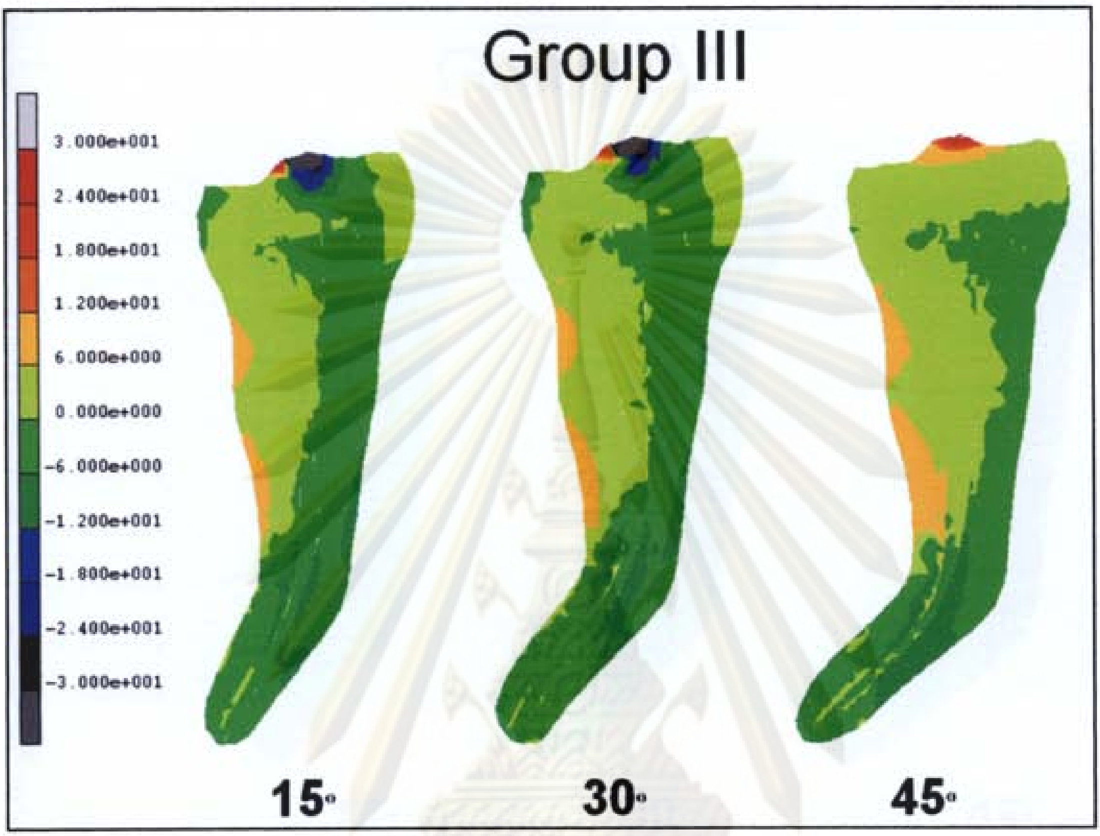

Fig. 12. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case I in mesio-distal plane of group III (prepared root canal and restored with resin composite core and porcelain fused to metal crowns) which was composed of the eighth to the tenth model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

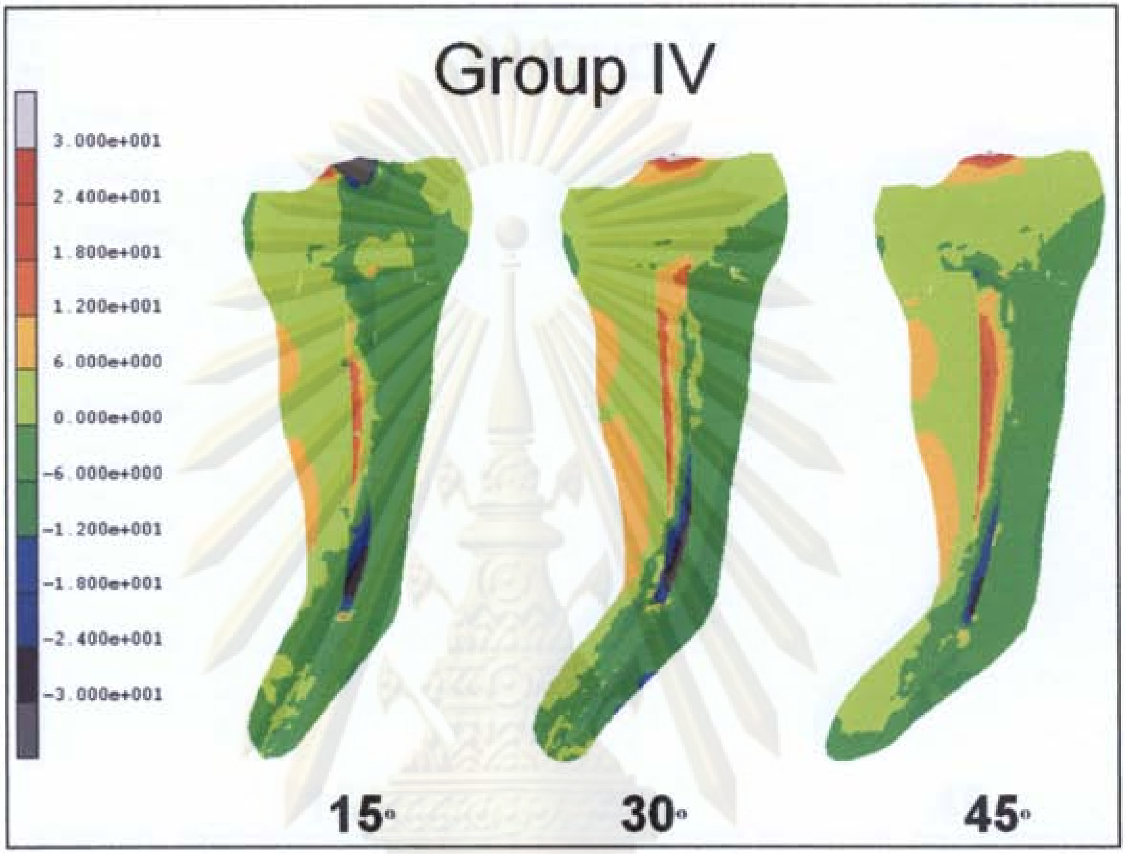

Fig. 13. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case I in mesio-distal plane of group IV (prepared root canal and restored with cast post and core and porcelain fused to metal crowns) which was composed of the eleventh to the thirteenth model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

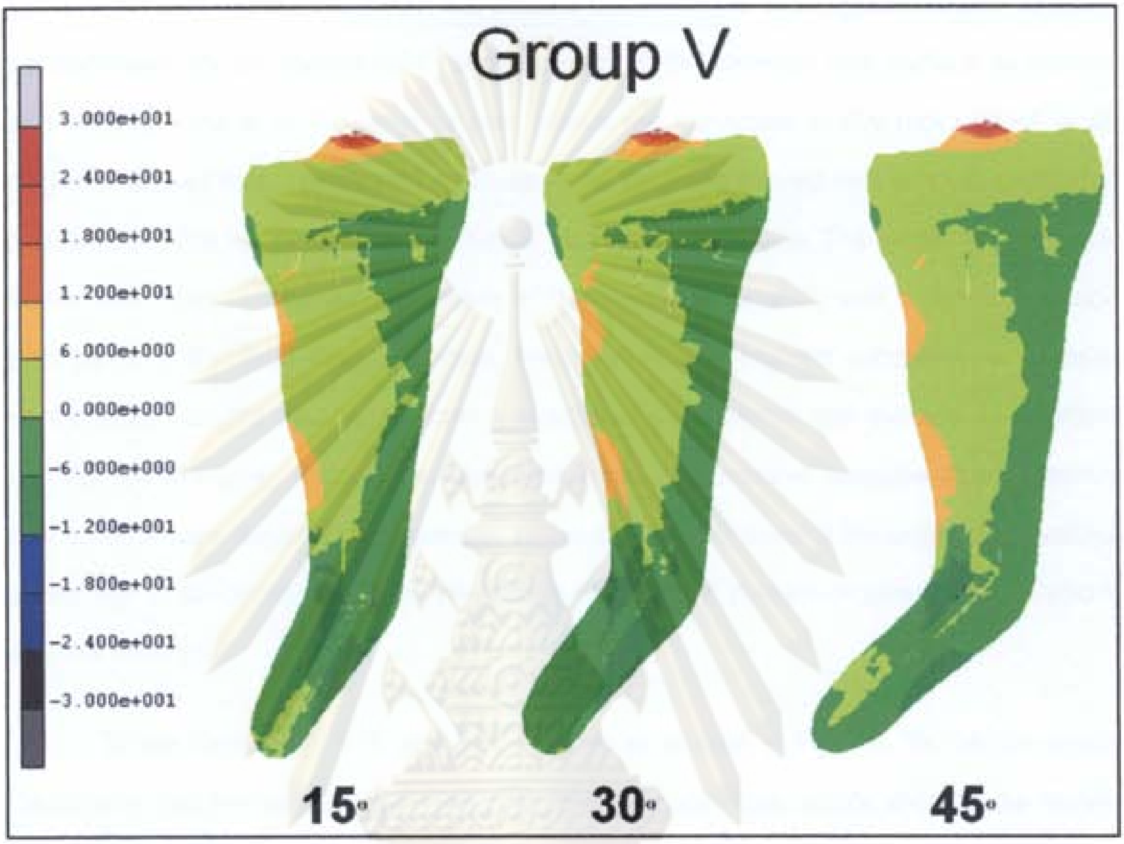

Fig. 14. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case I in mesio-distal plane of group V (prepared root canal and restored with prefabricated cylindrical post (glass-fiber) with composite core and porcelain fused to metal crowns) which was composed of the fourteenth to the sixteenth model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

The results from load case II models of group I, II, III and V were shown in Fig. 15, 16, 17 and 19 respectively. The results showed that the highest tensile stresses concentrated on the mesial side (convex side) of the external root surface at coronal and middle third or in the straight part above the curvature of the root except in 45 degrees curved root. The tensile stresses in 45 degrees curved root models expanded downward to the apical third of the mesial external root surface. The results showed that the tensile stress concentrations were in the opposite location and higher magnitude than those in the load case I models. Furthermore, the highest compressive stresses concentrated on the distal side (concave side) of the external root surface. In addition, as degrees of curved roots were increased, more compressive stresses at the external root surface were expanded downward to the apical third around the angle of curvature, especially in 45-degree models. The stress distribution pattern of group I, II, III and V was not different.

In the load case II of group IV models as shown in Fig. 18, the tensile stress distribution pattern was different from the other groups. The results showed the tensile stresses in both external root surface and internal root canal wall. The tensile stress concentration and location at the external root surface were the same as the other groups in load case II. Not only there were the tensile stresses at the external root surface, but the highest tensile stress concentrations were also found specifically on the post-dentin interface. This tensile stress concentration was much higher than those at the external root surface. In addition, as degrees of curved roots were increased, more tensile stress concentrations were increased on post-dentin interface. Furthermore the characteristics of compressive stress concentrations were on the distal side (or the concave side) of the external root surface in the same manners of the other groups. The stress distribution in load case II of each group was shown in Fig. 15-19.

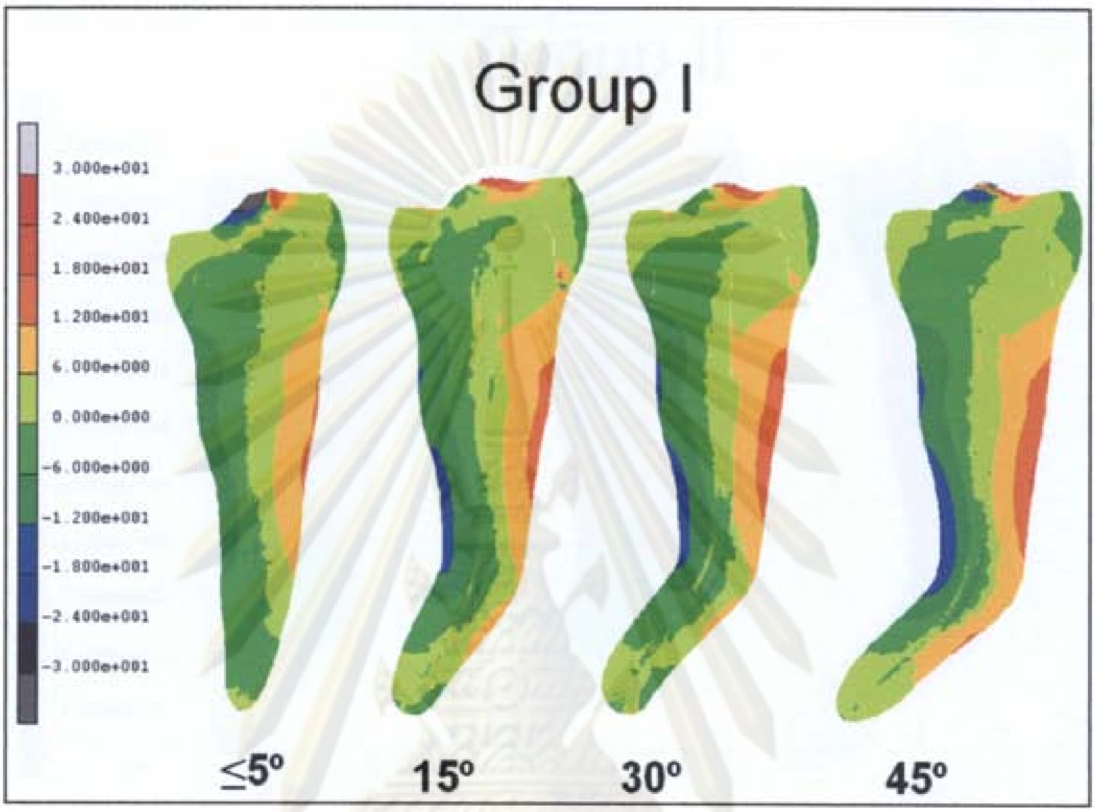

Fig. 15. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case II in mesio-distal plane of group I (control, non-RCT tooth) which was composed of the first to the fourth model that had curved roots at less than 5°, 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

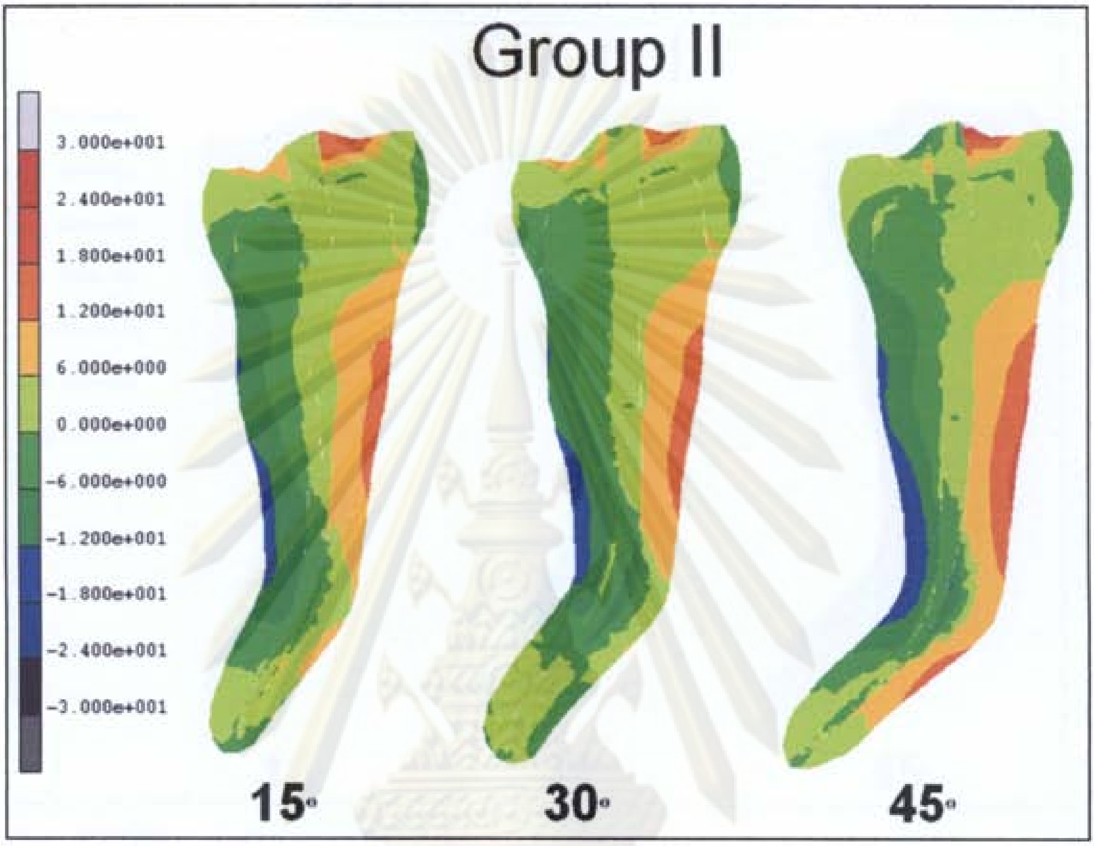

Fig. 16. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case II in mesio-distal plane of group II (prepared root canal and restored with resin composite) which was composed of the fifth to the seventh model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

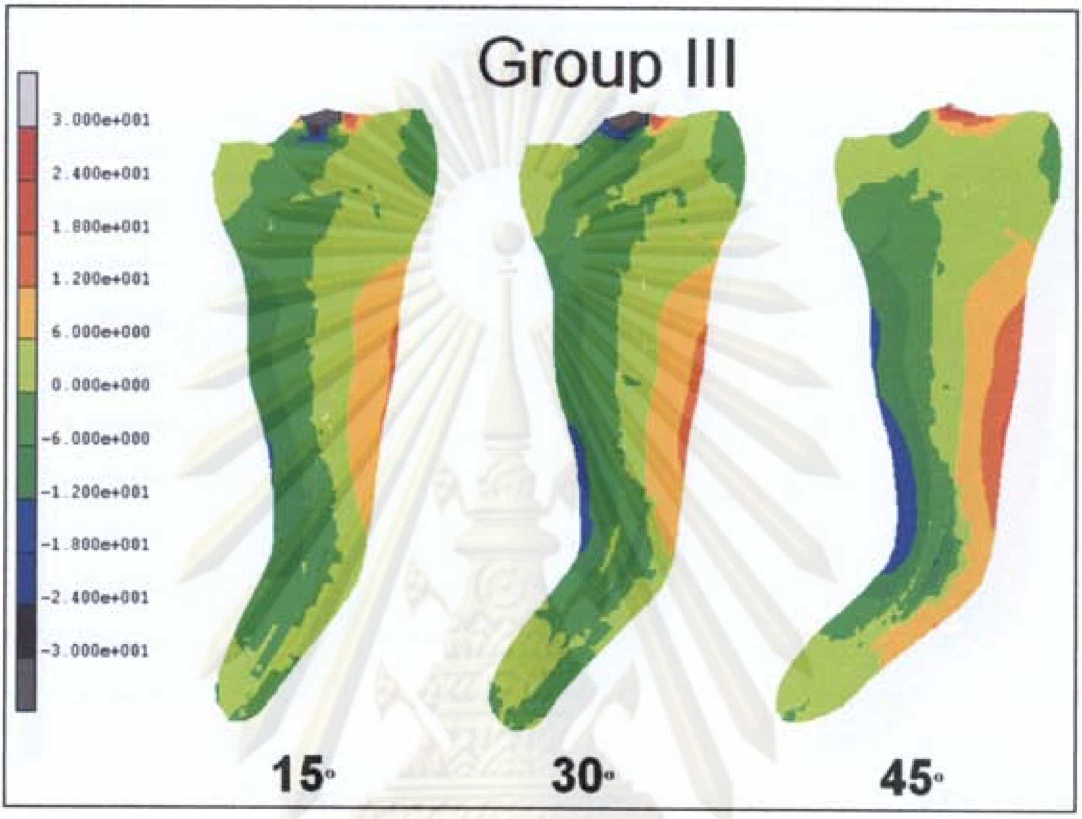

Fig. 17. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case II in mesio-distal plane of group III (prepared root canal and restored with resin composite core and porcelain fused to metal crowns) which was composed of the eighth to the tenth model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

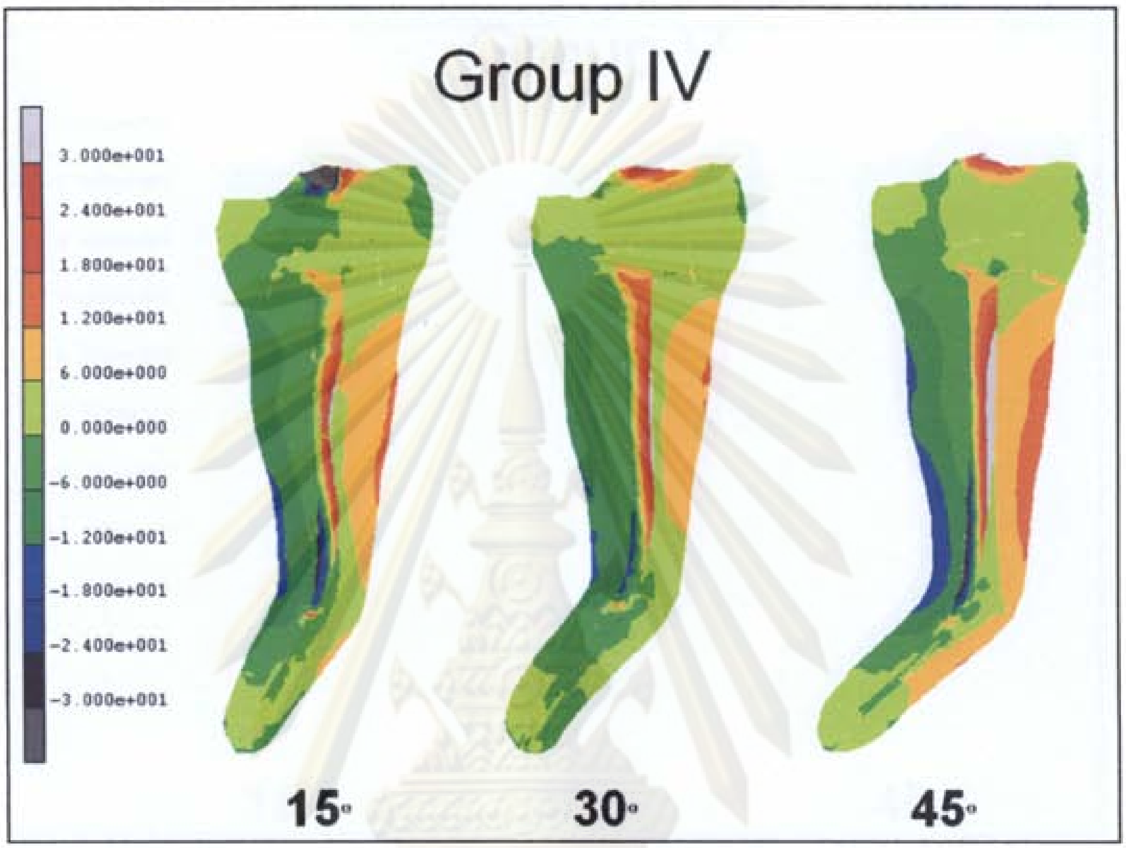

Fig. 18. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case II in mesio-distal plane of group IV (prepared root canal and restored with cast post and core and porcelain fused to metal crowns) which was composed of the eleventh to the thirteenth model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

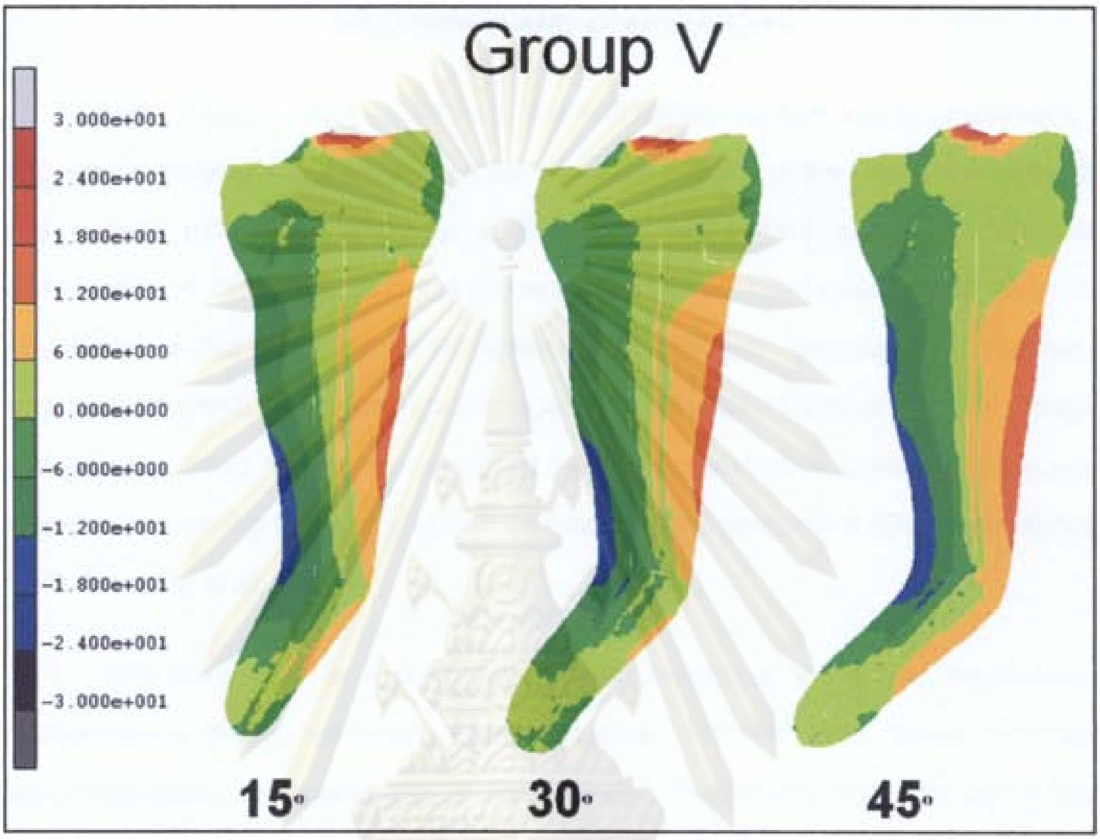

Fig. 19. Distribution of tensile (positive) and compressive (negative) stresses (MPa) in load case II in mesio-distal plane of group V (prepared root canal and restored with prefabricated cylindrical post (glass-fiber) with composite core and porcelain fused to metal crowns) which was composed of the fourteenth to the sixteenth model that had curved roots at 15°, 30° and 45°, respectively. Areas with same color were subjected to same range of stresses, as shown in the figure.

CHAPTER V

DISCUSSION AND CONCLUSIONS

Loss of enamel and dentin as a result of caries, fracture, cavity preparation, or endodontic therapy may compromise the structural integrity of the tooth. In addition, the complicated root canal anatomy such as severe curved root may cause the complication of root canal treatment procedures and may need specific restoration. It is usually known that posts do not strengthen teeth. However, they need for retention of core material which is replaced the damaged tooth structure (Assif *et al.*, 1989; Sedgley and Messer, 1992). In fact, some studies have indicated that in some situations posts might be detrimental to the strength of the tooth and restoration unit (Guzy and Nicholls, 1979; Standlee *et al.*, 1978).

This study tried to support for decision making in the proper restoration of endodontically treated teeth with various degrees of curved roots. Stress distribution was investigated and compared in each model. The results from this study might suggest the suitable restoration in endodontically treated tooth with curved root to avoid the stress concentration that could produce root fracture.

The three-dimensional models of the mandibular second premolars with various degrees of curved roots and different post systems were constructed for improving the approximation of reality based on external anatomy. These models simulated the round canal preparation for reducing the effects of root canal shapes (Lertchirakarn *et al.*, 2003a; Sathorn *et al.*, 2005b).

The 50 N load (load case I) was applied at 60° with long axis in buccolingual plane represented a high biting force (Rundquist and Versluis, 2006). The other 50 N load (load case II) was applied in the same direction of the root curvature. This load was represented in the tooth that having buccolingual curved root or rotated tooth that the curved root was in the same as force direction. These could make the direction of force go through the curved roots. Considerably these high loads may occur in some clinical or functional situations. However, the corresponding calculated stresses would change proportionally with the applied load.

An important advantage of using a finite element analysis is that all conditions can be kept exactly identical (such as tooth morphology, mechanical properties, load, periodontal support, etc.). Furthermore, the numerical method ensures that the root canal preparation has exactly the same size and taper in each model, which could have been more difficult to achieve in an experiment study in human teeth. It is speculated that this valuable theoretical tool will find more fields of application in biomechanics. Theoretically, FEA is very useful to study the mechanisms in which experimental techniques are impossible to apply. In addition, previous study has shown that the FEA is reasonably reliable in prediction of fracture patterns (Lertchirakarn *et al.*, 2003a). However, it is only numerical method to calculate from average material properties.

The results from this study in the load case I models, the highest tensile stress concentration in group I, II, III and V was found on the external root surface. Furthermore, the tensile stress concentrations in these groups were not found in the root canal wall. The tensile stress distributions were in the same pattern and magnitude as those in group I which was the control group (without root canal treatment and any restoration). The explanation of these results may be because modulus of elasticity of the restorative materials used in group II, III and V such as resin composite and glass fiber post are close to the dentin. This, theoretically makes stress distribution more uniform and distributes through root canal wall to the outer dentin. It is likely that these restorative materials behave like a single unit as root dentin. This explanation also explained that why there was no tensile stress concentration in the root canal or interface between restorative materials and root dentin. In contrast, tensile stress distribution in group IV was different from the others both in term of magnitude and location. In cast post and core system (group IV), not only the tensile stress concentration was found on the external root surface, it was also found on the post-dentin interface with higher magnitude than other groups. This study was in agreement with the previous studies (Nakamura *et al.*, 2006; Pegoretti *et al.*, 2002). In addition, the high tensile stress concentration was found at the post apex in this group. Thus, the cast posts, with a high modulus of elasticity, can cause a large stress concentration at the post-dentin interface along the root canal wall and at the post apex. It has been suggested that the high difference of elastic modulus of dentin and post materials can cause the high stress concentration due to asymmetrical distribution of stress through root dentin and becomes a source of stress for the root structures (Pegoretti *et al.*, 2002).

The results from the load case I models also suggested that the degree of root curvature affected only to expand area of stress concentration but not in stress magnitude in group I, II, III and V. This was different from group IV (cast post) which the pattern and magnitude was increased (Fig. 13).

The pattern of tensile stress concentrations in group I, II, III and V on the external root surface implied that the origin of root fracture might start from the external root surface in these groups. In contrast, the highest tensile stress concentration in group IV was shown on the post-dentin interface, especially when degree of root curvature increased. The cast post and core restoration with severe root curvature made that root was more prone to fracture. It was suggested that crack or root fracture was possible to originate from internal root canal wall rather than from external root surface in this case.

In the load case II models, the results from group I (nonendodontically treated teeth) showed that as degrees of curved roots were increased, more tensile stresses were found at the external root surface and distributed downward to the apical third. This implied that the degree of curved root influenced to stress distribution pattern, when the direction of load was in the same direction as root curvature. This result was also supported from the previous study that higher stresses tended to occur with the distal loading that was the same direction as the root curvature (Cheng *et al.*, 2007). In restoration of endodontically treated teeth with resin composite, resin composite with PFM crowns and prefabricated cylindrical glass fiber post with resin composite core and PFM crowns (group II, III and V) showed the highest tensile stress concentration at the external root surface. The stress distribution pattern in these groups were similar to the group I because modulus of elasticity of resin composite and glass fiber reinforced post were close to the dentin. In cast post and core system (group IV), the high tensile stress concentration areas were presented both at the external root surface and at the post-dentin interface. The results from this study were in agreement with the reports from previous studies that cast posts with a high modulus of elasticity could cause a large stress concentration at the post-dentin interface (Nakamura *et al.*, 2006; Pegoretti *et al.*, 2002). In addition, the high tensile stress concentration was found at the post apex in this group. In contrast, tensile stresses on the post-dentin interface were lower with the glass fiber posts than the cast posts. It has been suggested that the difference between elastic modulus of dentin and post materials is a cause of stress concentration in the root structures. The rigid post can resist forces and transfers the stress to the interface between post and tooth structure, this cause failure of the tooth structure (Mannocci *et al.*, 1999). Recently, it has been suggested that an ideal post should have a modulus of elasticity close to that of root dentin to avoid root fracture (Akkayan and Gulmez, 2002; Assif *et al.*, 1989; Pegoretti *et al.*, 2002).

The pattern of root fracture of group I, II, III and V in both load case I and II was predicted to originate from the external root surface. However, the pattern of root fracture in group IV (cast posts) was predicted to originate from internal root canal wall both along interface between post and dentin, and dentin at post apex together with the external root surface. Therefore, vertical and oblique or horizontal root fracture has tended to occur in the cast post and core restoration rather than other types of restoration in this study, especially in severe curved root.

In clinical situation, the prepared root canal may be still irregular because the mechanical instrumentation procedure does not touch the whole root canal wall although the rotary NiTi file has been used. This is because of the variation of root canal morphology. Thus, stress distribution is no longer uniform. Previous study by Lertchirakarn and co-workers (2003) reported that the root canal shape and root morphology could affect the stress distribution resulted in an increased tensile stress on the internal root canal wall. In addition, there are many factors that affect fracture susceptibility and pattern of fracture such as dentin thickness, curvature of the external proximal root surface, canal size and shape (Sathorn *et al.*, 2005b). All these factors relate to high stress concentration in the canal wall. In this study, the degree of root curvature also was a factor to cause high stress concentration areas not only in the root canal wall, post apex but also on the outer root surface in the case that restored with cast post core and crown.

The results from this study suggested that the direction of force and degree of root curvature might affect the stress distribution pattern and magnitude, especially in the case that restored with materials which had high different modulus of elasticity to those of dentin such as cast post and core. The degree of root curvature and direction of force had a little effect on magnitude but not in the pattern of stress distribution, when the materials used in restoration had modulus of elasticity close to those of dentin. In addition, this study suggested that the suitable restoration of endodontically treated lower premolar with limited loss of tooth structure, intact marginal ridge and ideal access opening was resin composite that was filled in the coronal third of root canal (4 mm from CEJ). However, in case that the post and core were needed, the glass-fiber post and resin composite core were the materials of choice.

Within the limitations of this study, it suggests that restoration in endodontically treated tooth with curved root canal especially in more than thirty degrees should be glass-fiber post and composite core with crown or resin composite. The cast post and core with crown restoration should not be used for restoration in curved root of endodontically treated tooth. Further studies are warranted to assess the validity of finite element analysis by ex-vivo study.

Conclusions

Within the limitations of this theoretical study, the following conclusions were drawn

1. Degrees of root curvature in this study (15°, 30° and 45°) had a little effect on the stress distribution pattern except when the direction of force was the same as the root curvature, the degrees of root curvature would affect both the stress distribution pattern and magnitude.

2. When the modulus of elasticity of the post and core materials used in this study was close to the root dentin, the highest tensile stress concentration was found only on the external root surface.

3. When the modulus of elasticity of the post and core materials used in this study was higher than the root dentin (cast post and core), the highest tensile stress concentration was found both on the post-dentin interface and at post apex. Vertical or horizontal root fracture might occur in this condition.

4. In accordance with data available in the literature (Pegoretti *et al.*, 2002), our study supported that if the post and core were needed, the glass fiber post and resin composite core were the materials of choice in endodontically treated premolar especially with curved root.

5. This study suggested that the suitable restoration should be for endodontically treated premolar with opening only ideal access was resin composite filled in the coronal third of the root canal.

References

Abou-Rass, M. 1983. Crack lines: the precursors of tooth fractures - their diagnosis and treatment. Quintessence Int Dent Dig 14(4):437-447.

Akkayan, B., and Gulmez, T. 2002. Resistance to fracture of endodontically treated teeth restored with different post systems. J Prosthet Dent 87(4):431-437.

al-Omari, M. A., Dummer, P. M., Newcombe, R. G., and Doller, R. 1992. Comparison of six files to prepare simulated root canals. 2. Int Endod J 25(2):67-81.

Al Wazzan, K. A. 2002. Effect of three endodontic materials on the bond strength of two composite core materials to dentin. J Prosthodont 11(2):92-97.

Aquilino, S. A., and Caplan, D. J. 2002. Relationship between crown placement and the survival of endodontically treated teeth. J Prosthet Dent 87(3):256-263.

Arola, D., Galles, L. A., and Sarubin, M. F. 2001. A comparison of the mechanical behavior of posterior teeth with amalgam and composite MOD restorations. J Dent 29(1):63-73.

Ash, M. M., and Wheeler, R. C. 1993. Wheeler's dental anatomy, physiology, and occlusion. 7th ed. Philadelphia: W.B. Saunders.

Assif, D., Oren, E., Marshak, B. L., and Aviv, I. 1989. Photoelastic analysis of stress transfer by endodontically treated teeth to the supporting structure using different restorative techniques. J Prosthet Dent 61(5):535-543.

Bartlett, S. O. 1968. Construction of detached core crowns for pulpless teeth in only two sittings. J Am Dent Assoc 77(4):843-845.

Bergman, B., Lundquist, P., Sjogren, U., and Sundquist, G. 1989. Restorative and endodontic results after treatment with cast posts and cores. J Prosthet Dent 61(1):10-15.

Boudrias, P., Sakkal, S., and Petrova, Y. 2001. Anatomical post design meets quartz fiber technology: rationale and case report. Compend Contin Educ Dent 22(4):337-340, 342, 344 passim; quiz 350.

Bryant, S. T., Thompson, S. A., al-Omari, M. A., and Dummer, P. M. 1998. Shaping ability of ProFile rotary nickel-titanium instruments with ISO sized tips in simulated root canals: Part 2. Int Endod J 31(4):282-289.

Caputo, A. A., and Standlee, J. P. 1976. Pins and posts--why, when and how. Dent Clin North Am 20(2):299-311.

Chan, C. P., Tseng, S. C., Lin, C. P., Huang, C. C., Tsai, T. P., and Chen, C. C. 1998. Vertical root fracture in nonendodontically treated teeth--a clinical report of 64 cases in Chinese patients. J Endod 24(10):678-681.

Chan, F. W., Harcourt, J. K., and Brockhurst, P. J. 1993. The effect of post adaptation in the root canal on retention of posts cemented with various cements. Aust Dent J 38(1):39-45.

Cheng, R., Zhou, X. D., Liu, Z., and Hu, T. 2007. Development of a finite element analysis model with curved canal and stress analysis. J Endod 33(6):727-731.

Cheung, W. 2005. A review of the management of endodontically treated teeth. Post, core and the final restoration. J Am Dent Assoc 136(5):611-619.

Christensen, G. J. 1998. Posts and cores: state of the art. J Am Dent Assoc 129(1):96-97.

Cohen, S., Blanco, L., and Berman, L. 2003. Vertical root fractures: clinical and radiographic diagnosis. J Am Dent Assoc 134(4):434-441.

Cohen, S., and Hargreaves, K. M. 2006. Pathways of the pulp. 9th ed. St. Louis, Mo.: Mosby Elsevier.

Dang, D. A., and Walton, R. E. 1989. Vertical root fracture and root distortion: effect of spreader design. J Endod 15(7):294-301.

Davy, D. T., Dilley, G. L., and Krejci, R. F. 1981. Determination of stress patterns in root-filled teeth incorporating various dowel designs. J Dent Res 60(7):1301-1310.

Derand, T. 1977. The principal stress distribution in a root with a loaded post in model experiments. J Dent Res 56(12):1463-1467.

Farah, J. W., Craig, R. G., and Sikarskie, D. L. 1973. Photoelastic and finite element stress analysis of a restored axisymmetric first molar. J Biomech 6(5):511-520.

Farah, J. W., Dennison, J. B., and Powers, J. M. 1977. Effects of design on stress distribution of intracoronal gold restorations. J Am Dent Assoc 94(6):1151-1154.

Feiglin, B. 1995. Clinical management of transverse root fractures. Dent Clin North Am 39(1):53-78.

Geurtsen, W., Schwarze, T., and Gunay, H. 2003. Diagnosis, therapy, and prevention of the cracked tooth syndrome. Quintessence Int 34(6):409-417.

Goldrich, N. 1970. Construction of posts for teeth with existing restorations. J Prosthet Dent 23(2):173-176.

Goodacre, C. J., and Spolnik, K. J. 1995. The prosthodontic management of endodontically treated teeth: a literature review. Part II. Maintaining the apical seal. J Prosthodont 4(1):51-53.

Gupta, K. K., Knoell, A. C., and Grenoble, D. E. 1973. Mathematical modeling and structural analysis of the mandible. Biomater Med Devices Artif Organs 1(3):469-479.

Gutmann, J. L. 1992. The dentin-root complex: anatomic and biologic considerations in restoring endodontically treated teeth. J Prosthet Dent 67(4):458-467.

Guzy, G. E., and Nicholls, J. I. 1979. In vitro comparison of intact endodontically treated teeth with and without endo-post reinforcement. J Prosthet Dent 42(1):39-44.

Hedlund, S. O., Johansson, N. G., and Sjogren, G. 2003. Retention of prefabricated and individually cast root canal posts in vitro. Br Dent J 195(3):155-158; discussion 147.

Henry, P. J. 1977. Photoelastic analysis of post core restorations. Aust Dent J 22(3):157-159.

Heydecke, G., Butz, F., and Strub, J. R. 2001. Fracture strength and survival rate of endodontically treated maxillary incisors with approximal cavities after restoration with different post and core systems: an in-vitro study. J Dent 29(6):427-433.

Hirschfeld, Z., and Stern, N. 1972. Post and core--the biomechanical aspect. Aust Dent J 17(6):467-468.

Ho, M. H., Lee, S. Y., Chen, H. H., and Lee, M. C. 1994. Three-dimensional finite element analysis of the effects of posts on stress distribution in dentin. J Prosthet Dent 72(4):367-372.

Holmes, D. C., Diaz-Arnold, A. M., and Leary, J. M. 1996. Influence of post dimension on stress distribution in dentin. J Prosthet Dent 75(2):140-147.

Hood, J. A., Farah, J. W., and Craig, R. G. 1975. Modification of stresses in alveolar bone induced by a tilted molar. J Prosthet Dent 34(4):415-421.

Ichikawa, Y., Akagawa, Y., Nikai, H., and Tsuru, H. 1992. Tissue compatibility and stability of a new zirconia ceramic in vivo. J Prosthet Dent 68(2):322-326.

Johnson, J. K., Schwartz, N. L., and Blackwell, R. T. 1976. Evaluation and restoration of endodontically treated posterior teeth. J Am Dent Assoc 93(3):597-605.

Kane, J. J., and Burgess, J. O. 1991. Modification of the resistance form of amalgam coronal-radicular restorations. J Prosthet Dent 65(4):470-474.

Lertchirakarn, V., Palamara, J. E., and Messer, H. H. 2003a. Patterns of vertical root fracture: factors affecting stress distribution in the root canal. J Endod 29(8):523-528.

Lertchirakarn, V., Palamara, J. E., and Messer, H. H. 2003b. Finite element analysis and strain-gauge studies of vertical root fracture. J Endod 29(8):529-534.

Lewgoy, H. R., Youssef, M. N., Matson, M. R., Bocangel, J. A., Netto, C. A., and Amore, R. 2003. Finite elements study of the Flexi Post and Flexi Flange post systems in a maxillary central incisor. Pesqui Odontol Bras 17(2):132-136.

Logan, D. L., and Logan, D. L. 2002. A first course in the finite element method. 3rd ed. Pacific Grove, CA: Brooks/Cole.

Mannocci, F., Innocenti, M., Ferrari, M., and Watson, T. F. 1999. Confocal and scanning electron microscopic study of teeth restored with fiber posts, metal posts, and composite resins. J Endod 25(12):789-794.

Mannocci, F., Ferrari, M., and Watson, T. F. 2001. Microleakage of endodontically treated teeth restored with fiber posts and composite cores after cyclic loading: a confocal microscopic study. J Prosthet Dent 85(3):284-291.

Mannocci, F., Bertelli, E., Sherriff, M., Watson, T. F., and Ford, T. R. 2002. Three-year clinical comparison of survival of endodontically treated teeth restored with either full cast coverage or with direct composite restoration. J Prosthet Dent 88(3):297-301.

Martin, H., and Fischer, E. 1990. Photoelastic stress comparison of warm (Endotec) versus cold lateral condensation techniques. Oral Surg Oral Med Oral Pathol 70(3):325-327.

Meister, F., Jr., Lommel, T. J., and Gerstein, H. 1980. Diagnosis and possible causes of vertical root fractures. Oral Surg Oral Med Oral Pathol 49(3):243-253.

Mezzomo, E., Massa, F., and Libera, S. D. 2003. Fracture resistance of teeth restored with two different post-and-core designs cemented with two different cements: an in vitro study. Part I. Quintessence Int 34(4):301-306.

Morfis, A. S. 1990. Vertical root fractures. Oral Surg Oral Med Oral Pathol 69(5):631-635.

Morgano, S. M. 1996. Restoration of pulpless teeth: application of traditional principles in present and future contexts. J Prosthet Dent 75(4):375-380.

Nakamura, T., *et al.* 2006. Stress analysis of endodontically treated anterior teeth restored with different types of post material. Dent Mater J 25(1):145-150.

Naumann, M., Rosentritt, M., Preuss, A., and Dietrich, T. 2006. The effect of alveolar bone loss on the load capability of restored endodontically treated teeth: a comparative in vitro study. J Dent 34(10):790-795.

Neumann, H. H., and Disalvo, N. A. 1957. Compression of teeth under the load of chewing. J Dent Res 36(2):286-290.

Newburg, R. E., and Pameijer, C. H. 1976. Retentive properties of post and core systems. J Prosthet Dent 36(6):636-643.

Newman, M. P., Yaman, P., Dennison, J., Rafter, M., and Billy, E. 2003. Fracture resistance of endodontically treated teeth restored with composite posts. J Prosthet Dent 89(4):360-367.

Noonan, M. A. 1949. The use of photoelasticity in a study of cavity preparations. J Dent Child 16(4):24-28, illust.

Oyama, K., Motoyoshi, M., Hirabayashi, M., Hosoi, K., and Shimizu, N. 2007. Effects of root morphology on stress distribution at the root apex. Eur J Orthod 29(2):113-117.

Panitvisai, P., and Messer, H. H. 1995. Cuspal deflection in molars in relation to endodontic and restorative procedures. J Endod 21(2):57-61.

Pegoretti, A., Fambri, L., Zappini, G., and Bianchetti, M. 2002. Finite element analysis of a glass fibre reinforced composite endodontic post. Biomaterials 23(13):2667-2682.

Perez Moll, J. F., Howe, D. F., and Svare, C. W. 1978. Cast gold post and core and pin-retained composite resin bases: a comparative study in strength. J Prosthet Dent 40(6):642-644.

Pitts, D. L., and Natkin, E. 1983. Diagnosis and treatment of vertical root fractures. J Endod 9(8):338-346.

Qualtrough, A. J., Chandler, N. P., and Purton, D. G. 2003. A comparison of the retention of tooth-colored posts. Quintessence Int 34(3):199-201.

Reeh, E. S., Messer, H. H., and Douglas, W. H. 1989. Reduction in tooth stiffness as a result of endodontic and restorative procedures. J Endod 15(11):512-516.

Reinhardt, R. A., Krejci, R. F., Pao, Y. C., and Stannard, J. G. 1983. Dentin stresses in post-reconstructed teeth with diminishing bone support. J Dent Res 62(9):1002-1008.

Ricks-Williamson, L. J., Fotos, P. G., Goel, V. K., Spivey, J. D., Rivera, E. M., and Khera, S. C. 1995. A three-dimensional finite-element stress analysis of an endodontically prepared maxillary central incisor. J Endod 21(7):362-367.

Rolf, K. C., Parker, M. W., and Pelleu, G. B. 1992. Stress analysis of five prefabricated endodontic dowel designs: a photoelastic study. Oper Dent 17(3):86-92.

Rosenstiel, S. F., Land, M. F., and Fujimoto, J. 2001. Contemporary fixed prosthodontics. 3rd ed. St. Louis, Mo.: Mosby.

Rubin, C., Krishnamurthy, N., Capilouto, E., and Yi, H. 1983. Stress analysis of the human tooth using a three-dimensional finite element model. J Dent Res 62(2):82-86.

Rundquist, B. D., and Versluis, A. 2006. How does canal taper affect root stresses? Int Endod J 39(3):226-237.

Sathorn, C., Palamara, J. E., and Messer, H. H. 2005a. A comparison of the effects of two canal preparation techniques on root fracture susceptibility and fracture pattern. J Endod 31(4):283-287.

Sathorn, C., Palamara, J. E., Palamara, D., and Messer, H. H. 2005b. Effect of root canal size and external root surface morphology on fracture susceptibility and pattern: a finite element analysis. J Endod 31(4):288-292.

Saw, L. H., and Messer, H. H. 1995. Root strains associated with different obturation techniques. J Endod 21(6):314-320.

Schneider, S. W. 1971. A comparison of canal preparations in straight and curved root canals. Oral Surg Oral Med Oral Pathol 32(2):271-275.

Sedgley, C. M., and Messer, H. H. 1992. Are endodontically treated teeth more brittle? J Endod 18(7):332-335.

Shillingburg, H. T., Jr., Fisher, D. W., and Dewhirst, R. B. 1970. Restoration of endodontically treated posterior teeth. J Prosthet Dent 24(4):401-409.

Sirimai, S., Riis, D. N., and Morgano, S. M. 1999. An in vitro study of the fracture resistance and the incidence ofvertical root fracture of pulpless teeth restored with six post-and-coresystems. J Prosthet Dent 81(3):262-269.

Smith, C. T., and Schuman, N. 1998. Prefabricated post-and-core systems: an overview. Compend Contin Educ Dent 19(10):1013-1018, 1020; quiz 1022.

Sorensen, J. A., and Martinoff, J. T. 1984. Intracoronal reinforcement and coronal coverage: a study of endodontically treated teeth. J Prosthet Dent 51(6):780-784.

Standlee, J. P., Caputo, A. A., Collard, E. W., and Pollack, M. H. 1972. Analysis of stress distribution by endodontic posts. Oral Surg Oral Med Oral Pathol 33(6):952-960.

Standlee, J. P., Caputo, A. A., and Hanson, E. C. 1978. Retention of endodontic dowels: effects of cement, dowel length, diameter, and design. J Prosthet Dent 39(4):400-405.

Standlee, J. P., Caputo, A. A., Holcomb, J., and Trabert, K. C. 1980. The retentive and stress-distributing properties of a threaded endodontic dowel. J Prosthet Dent 44(4):398-404.

Standlee, J. P., and Caputo, A. A. 1992. Endodontic dowel retention with resinous cements. J Prosthet Dent 68(6):913-917.

Stern, N., and Hirshfeld, Z. 1973. Principles of preparing endodontically treated teeth for dowel and core restorations. J Prosthet Dent 30(2):162-165.

Tait, C. M., Ricketts, D. N., and Higgins, A. J. 2005. Restoration of the root-filled tooth: pre-operative assessment. Br Dent J 198(7):395-404.

Takahashi, N., Kitagami, T., and Komori, T. 1980. Behaviour of teeth under various loading conditions with finite element method. J Oral Rehabil 7(6):453-461.

Tamse, A., Fuss, Z., Lustig, J., and Kaplavi, J. 1999. An evaluation of endodontically treated vertically fractured teeth. J Endod 25(7):506-508.

Terry, D. A., Triolo, P. T., Jr., and Swift, E. J., Jr. 2001. Fabrication of direct fiber-reinforced posts: a structural design concept. J Esthet Restor Dent 13(4):228-240.

Tjan, A. H., Grant, B. E., and Dunn, J. R. 1991. Microleakage of composite resin cores treated with various dentin bonding systems. J Prosthet Dent 66(1):24-29.

Toksavul, S., Zor, M., Toman, M., Gungor, M. A., Nergiz, I., and Artunc, C. 2006. Analysis of dentinal stress distribution of maxillary central incisors subjected to various post-and-core applications. Oper Dent 31(1):89-96.

Trope, M., Maltz, D. O., and Tronstad, L. 1985. Resistance to fracture of restored endodontically treated teeth. Endod Dent Traumatol 1(3):108-111.

Trope, M., and Rosenberg, E. S. 1992. Multidisciplinary approach to the repair of vertically fractured teeth. J Endod 18(9):460-463.

Vire, D. E. 1991. Failure of endodontically treated teeth: classification and evaluation. J Endod 17(7):338-342.

Walton, R. E., Michelich, R. J., and Smith, G. N. 1984. The histopathogenesis of vertical root fractures. J Endod 10(2):48-56.

Walton, R. E., and Torabinejad, M. 2002. Principles and practice of endodontics. 3rd ed. Philadelphia: Saunders.

Yaman, S. D., Alacam, T., and Yaman, Y. 1995. Analysis of stress distribution in a vertically condensed maxillary central incisor root canal. J Endod 21(6):321-325.

Yang, H. S., Lang, L. A., Molina, A., and Felton, D. A. 2001. The effects of dowel design and load direction on dowel-and-core restorations. J Prosthet Dent 85(6):558-567.

Yang, S. F., Rivera, E. M., and Walton, R. E. 1995. Vertical root fracture in nonendodontically treated teeth. J Endod 21(6):337-339.

Zienkiewicz, O. C., Taylor, R. L., Zhu, J. Z., Zienkiewicz, O. C., Zienkiewicz, O. C., and Knovel (Firm) 2005. The finite element method its basis and fundamentals. Amsterdam ; Boston: Elsevier Butterworth-Heinemann, pp. xiv, 733 p., [734] p. of plates.

Zillich, R. M., and Corcoran, J. F. 1984. Average maximum post lengths in endodontically treated teeth. J Prosthet Dent 52(4):489-491.

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