THE FRACTURE RESISTANCE OF STRUCTURALLY COMPROMISED ROOTS USING DIFFERENT POST SYSTEMS

CS Solomon

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A mini-thesis submitted in partial fulfilment of the requirements for the M.Ch.D degree in the discipline of Prosthodontics to the Faculty of Dentistry, University of the Western Cape.

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Abstract

The Fracture Resistance Of Structurally Compromised Roots Using Different Post Systems

M.Ch.D mini-thesis, Department Conservative Dentistry, Faculty of Dentistry, University of the Western Cape

The structurally compromised root presents a great challenge to the restorative dentist. The amount of tooth structure that remains after endodontic therapy and post preparation is of prime importance and the strength of an endodontically treated tooth is directly related to the amount of residual dentine. Post and cores are often required with pulpless teeth to provide retention and resistance form for the final restoration. **Aim:** The purpose of this in vitro study is to investigate the fracture resistance of structurally compromised teeth using four dynamically different post and core systems in the rehabilitation process. **Method:** After the crowns were removed one specimens were then randomly divided into four groups of 25 teeth each as follow: Group A: morphologic cast post and core; Group B: resin reinforced glass-fibre post and composite core; Group C: resin reinforced carbon fibre post with composite core and Group D: resin reinforced prefabricated parallel-sided titanium post and composite core. All specimens were subjected to an increasing palatal force until fracture occurred. **Results:** Results showed cast post and cores to have higher fracture loads that the resin reinforced groups *(p* < 0). The difference in fracture resistance between the three reinforced groups was found not to be significant (*p* > 0). **Conclusions:** Significantly higher fracture thresholds were obtained in the cast post-and-core group. The reinforced group (with composite cores) showed failure of the post-core interface before the fracture of the tooth occurred. This failure occurred in response to acceptable high loads. The Luminex® light transmitting posts can help strengthen weakened, endodontically treated teeth by the combined bonding action of dentine bonding agents and composite resin restorative material.

Declaration

I, ………………………………………………………..declare that "The fracture resistance of structurally compromised roots using different post systems" is my own work and that all sources have been indicated and acknowledged by means of references.

Signed:…………………………………..

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Dedication

For Ashley and Melissa, my constant pillars of support,

and

To the memory of Professor Trevor Arendorf, whose enthusiasm for academic research has played a crucial role in my formative years as a research scholar.

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CHAPTER ONE: INTRODUCTION

The restoration of endodontically treated teeth has always presented a challenge to dental clinicians primarily because of coronal destruction from dental caries, fractures, and previous restorations or endodontic techniques. The loss of tooth structure frequently associated with endodondic treatment is accompanied by a reduction in the strength and capability of the tooth to resist various intra-oral forces. This predisposes the tooth to unwanted root fractures.

Most of the literature concerning the restoration of the endodontically treated tooth has focused on the post-core unit. The post is described as a unit that provides retention and resistance to dislodgement of the core material. The core is seen as the coronal extension of the post that simulates a prepared tooth to retain a definite cast restoration (Assif and Gorfil, 1994). The traditional objective for a post was to strengthen the weakened tooth. Post and cores are routinely advocated to (1) protect or strengthen the tooth against intra-oral forces by equally distributing torquing forces within the radicular dentine to supporting tissues, thus dispersing the forces along the root, and (2) provide retention for the core that replaces the lost coronal tooth structure which retains the restoration. The validity of these assumptions and the ability of the post to provide strength to the weakened tooth have been extensively researched and reported on in the dental literature (Assif and Gorfil, 1994; Christensen, 1996; KO, *et al*, 1992; Ross, 1980).

The bulk of the literature reports on and compares various post and core systems currently available from the dental suppliers (Brown and Mitchem, 1987; Chapman *et al*, 1985; Cohen *et al*, 1994; Cohen *et al*, 1997; Cohen *et al*, 1998; Cooney *et al*, 1986; Gateau *et al*, 1999; Isidør and Brøndum, 1992; Reagan *et al*, 1999; Wilson *et al*, 1997). However, most of these studies were done on teeth that closely resembled the ideal clinical situation, i.e., where adequate dentine existed to place anti-rotational locks or keyways, placement of ferrule bevels and post space diameters that readily accepted prefabricated posts. However, in the clinical situation, this is infrequently the case. Endodontic and post-and-core retreatment often result in wide diameter or flared canals. Traditionally, these wide canals were restored with cast posts for the simple reason that they were the only posts to provide a close fit within the prepared canal. However, wide tapered cast posts produce wedging forces in the apical third of the root, weakening the tooth and eventually fracturing the root.

The advent of adhesive dentistry has expanded the limited treatment modalities for the compromised root. These flared canals can now be restored and rehabilitated successfully with resin composite prior to the placement of a prefabricated post (Godder *et al*, 1994; Lui, 1994(a); Trushkowsky, 1995). Details regarding the techniques currently being employed are discussed later. Rehabilitation of the compromised root canal is now recognised as a clinically acceptable and satisfactory treatment modality. However, the literature does not distinguish amongst the various post systems for their suitability in specifically compromised root canals.

This paper attempts to address this very issue. The experimental study and the literature review will endeavour to bring together a variety of *in vitro* and *in vivo* studies, along with clinical technique articles and clinical reports to provide meaningful guidelines for the dental clinician when selecting methods and materials for the restoration of structurally compromised teeth.

CHAPTER TWO: LITERATURE REVIEW

2.1 The evolution of posts and post designs

The concept of using the root of a tooth for retention dates back to the eighteenth century when Fauchard (a French dentist) inserted wooden dowels into canals of teeth to aid crown retention. Wooden dowels would expand in the moist environment to enhance the retention of the dowel until unfortunately, the root would often fracture vertically. Several of the nineteenth century versions of dowels also used wooden "pivots", but some dentists reported the use of metal posts in which a porcelain-faced crown was secured by a screw passing into a gold-lined root canal.

The Richmond crown was introduced in 1878 and incorporated a threaded tube in the canal with a screw-retained crown. The Richmond crown was later modified to eliminate the threaded tube and was redesigned as a 1-piece dowel and crown. The one-piece dowel-crowns became unpopular because they were not practical. This was evident when divergent paths of insertion of the post-space and remaining tooth structure existed, especially for abutments of fixed partial dentures (FPDs). Retrievability was a frequent problem encountered with the one-piece dowel-crown restoration. These difficulties led to the development of a post-and-core restoration as a separate entity with an artificial crown cemented over a core and remaining tooth structure.

With the advent of scientific endodontic therapy in the 1950s, the challenges increased for restorative dentistry. Teeth that were commonly extracted without hesitation were successfully treated with predictable endodontic therapy, and a satisfactory restorative solution was then needed. Cast post and cores became routine methods for restoration of endodontically treated teeth (Morgano and Brackett, 1999). The custom cast post and core has traditionally been recommended for corono-radicular stabilization of the endodontically treated tooth. It has been used with great success, but drawbacks of this post system included post dislodgement (partly due to inadequate retention and too short a post) and root fractures (due to excessive taper of the post). In addition, cast post and core procedures are time-consuming (at least two visits) and expensive because of the laboratory procedures involved. Clinicians have desired a less time-consuming approach to coronoradicular stabilization and a simplified procedure to replace the laborious custom-cast post and core.

The expeditious features of the prefabricated post combined with cost-effectiveness have stimulated considerable interest and is currently the most popular method for post and core build up. Many studies have been conducted on the most acceptable shape for posts.

The desire for added retention prompted the development of the screw post. While it provides increased retention, this design requires care during insertion to avoid fracturing either the root or the post. According to Hudis and Goldstein (1986), photo-elastic studies have also demonstrated high levels of stress for the screw post in loaded and unloaded states. The high stresses involved during the tapping procedure at delivery increased the risk of fracture (Sorenson and Martinoff, 1984) and this method therefore became a poor alternative in the restoration of the endodontically treated tooth. Another variation on the internal design is the parallel-sided cylindrical post, which offers greater retention than the tapered posts and with more favourable stress distribution than screw posts. The parallel post can have a smooth or serrated surface.

Prefabricated posts with bonded composite or silver amalgam cores are faster and easier to construct than custom cast posts and cores. The additional provision of strength and serviceability at a relatively low cost to patients has made them extremely popular.

The demands of aesthetic dentistry have caused a shift towards metal-free post systems under all ceramic restorations. Newer metal-free post systems include carbon fiber, glass fiber and ceramic posts. The carbon- and glass fiber posts have also addressed the issue of easy post retrieval. When a metal post fractures or fails, it is virtually impossible to remove the residual post from the radicular structure of the tooth without greatly compromising the remaining dentine. Most current techniques involve enlarging the canal around the residual post until the post can be manipulated by a hand instrument. The channel enlargement usually removes so much dentine that the long-term prognosis for the tooth is compromised.

Post and post designs have come a long way since the wooden dowel and the one-piece Richmond crown. The newer designs provide increased strength and retention to the post-core unit and allow uncomplicated retrieval and improved aesthetics for all-ceramic restorations.

2.2 Objectives of post-and-core treatment

Traditionally, the primary objective of post-and-core build-up was to replace the missing coronal tooth structure sufficiently to provide the required retention and resistance form for the final restoration (the crown). The core build-up is dependent on the remaining supra-gingival tooth structure that is available for the restoration. If there is sufficient tooth structure remaining, post-and-core build-up may not be needed. However, if supra-gingival tooth structure is largely missing, the post-and-core build-up is an essential prerequisite to crown fabrication.

The main function of the post is to anchor the post-and-core complex within the radicular portion of the remaining tooth. A post that can be bonded to tooth structure has an improved ability to retain the entire foundation. The adhesive, tensile and shear strengths of the resin to both tooth and post materials assures the predictability and longevity of the restoration (Freedman, 2001). The post does not reinforce the root, nor does it extend any strength to the fragile remaining dentine. Therefore, post selection should be based on the one that provides maximum retention, while at the same time requiring minimal removal of the remaining sub-gingival tooth structure.

The core is described as a supra-gingival extension of the post. The core provides a visible and accessible platform for, to improve retention of, and to strategically manage the transfer of forces from the final restoration. Freedman (2001) describes the post-and-core complex as a restorative continuum monobloc. The latter multilayered structure with no inherent weak inter-layer interfaces can be created using current adhesive techniques and materials. The dentine is bonded to the resin cement, which is bonded to both the post and core materials. The prepared core and remaining peripheral tooth structure are then bonded to the final restoration through a dual-cure resin cement. Therefore, every component of tooth or restorative material is directly or indirectly bonded to every other component. The bonding strength at each interface is stronger than the bond of the tooth itself. Therefore, the integrity of the final endodontic restorative continuum monobloc approaches that of the original healthy tooth itself.

Factors that may affect treatment outcomes are the decreased moisture content and subsequent brittleness of pulpless teeth combined with the loss of both external and internal tooth structure making the unrestored tooth less resistant to stress and undesirable forces. The endodontically treated tooth also has a lowered resistance to decay due to loss of neural stimuli (Hudis and Goldstein, 1986). The restoration of the pulpless tooth should ideally increase the resistance to horizontal and vertical forces.

Recent studies have demonstrated a strong challenge of the post-and-core concept, with many clinicians stating that posts are almost never needed. If the anatomic crown is sufficiently preserved and core retention can be achieved from within the natural crown, a post is not necessary (Assif *et al*, 1993). The main reason for using posts is now recognized as to provide a connection between the missing coronal portion of the tooth and the remaining root structure, thereby providing retention for the crown (Christensen, 1996).

2.3 Types of Posts

2.3.1 Custom Cast Post and Cores

The development of cast post and cores was a logical evolution from the Richmond crown as reported by Morgano and Brackett (1999). Cast post and cores have been reported to provide excellent service for endodontically treated teeth with moderate to severe damage. Bergman and co-workers (1989) evaluated 96 endodontically treated teeth with extensive loss of tooth structure in a 6-year retrospective study. Their results showed custom cast posts to have a 90.6% success rate. This is primarily due to its high strength and increased resistance to fracture when compared to other post systems (Sirimai *et al*, 1999).

A disadvantage often described of the cast posts is their metallic gray color that poses an aesthetic problem in anterior all-ceramic restorations, particularly when a high lip or broad smile reveals the entire restoration. To overcome this problem, Zalkind and Hochman (1998) suggest using gold cast posts (gold provides a more favourable background for all-ceramic restorations than base metal posts). Another alternative is to coat the core with opaque ceramic to mask the metal (i.e. if a porcelain metal is used).

Even though many new post systems have been introduced, cast posts seem to be a popular treatment modality. A recent survey of current opinions among prosthodontists and general practitioners in Sweden showed that cast posts were the most commonly used post option (Eckerbom and Magnusson, 2001). This confirmed previous findings of a national survey in the United States where the majority of dentists used either cast posts exclusively or both cast posts and prefabricated posts in their practices (Morgano *et al*, 1994).

2.3.1.1 Methods of fabricating cast posts and cores

A reliable method for fabricating a custom post core is the direct fabrication of the pattern. The tooth is prepared for the crown after the existing restorations, dental caries, and weakened tooth structure are removed; the post space is then prepared. Guidelines for the length of the post include a length at least equal to the length of the clinical crown of the final restoration, and at least two thirds or three quarters the length of the root in bone (Stockton, 1999). *In vivo* studies have suggested that clinical success of posts is directly proportional to their lengths; so it is rational to prepare a post channel as long as it is consistent with anatomic limitations while maintaining 4 to 5 mm of apical gutta percha as a hermetic seal. A shorter post is undesirable since it is less retentive and can produce unfavorable leverage and shear stresses within the root canal that may predispose the root to fracture. The width of the post is also an important consideration since arbitrarily widening the diameter of the post will reduce the thickness and strength of the radicular dentin. Thickness of remaining dentin is critical.

The post space should provide resistance to rotation of the post core. If the configuration of the prepared canal is circular in cross section, it will not provide this resistance to rotation. A keyway should be placed within the canal. A positive seat for the core at the opening of the post-space is desirable to prevent overseating of the post, which may wedge the root and cause vertical fracture.

Morgano and Brackett (1999) described numerous materials used in the past for the fabrication of the post-core pattern. Materials included: wax with a plastic rod as a carrier and support, wax with a dental bur, and acrylic resin with a solid plastic sprue. Another method developed and described by Moragno and Brackett (1999) was a core of acrylic resin with an endodontic file coated with wax that adapted to the prepared canal. A variation of the direct custom post core incorporated a prefabricated plastic pattern manufactured to correspond to the diameter and configuration of a specific reamer. With this method, the desired reamer was used to instrument the canal, and the matching plastic pattern was inserted into the post channel. Acrylic resin was then adapted to the coronal surface of the post pattern and contoured to the desired form. These prefabricated plastic patterns can be divided into 2 types: (1) precision parallel posts and (2) precision tapered posts.

Custom cast post cores require 2 visits. A primary disadvantage of the direct method of fabricating posts and cores is the chair time to fabricate the pattern. The indirect method conserves chair time by delegating the pattern for the post and core to a dental laboratory technician. Nevertheless, an accurate impression of the prepared post space that extends deeply in the canal of an endodontically treated tooth is a challenge. Success of the indirect method depends on the accuracy of the impression replicating the internal surface of the prepared root canal. Impression material may be injected into the post space and distributed with a spiral paste filler to capture the internal morphology of the canal. A rigid object (e.g. a plastic impression post) is inserted into the canal before the initial set of impression material to strengthen this impression and minimize the potential for distortion

2.3.1.2 Alloys for cast posts and cores

Traditionally, custom dowel cores were cast in a gold alloy comparable to the alloys used for complete crowns. For decades the US government maintained a gold standard that resulted in a fixed, inexpensive price for gold. When this regulation for the price of gold was removed, the cost of gold elevated dramatically in the 1970s. With the cost of gold at unprecedented levels, there was an incentive to develop alternative alloys for cast restorations, including post cores. Base metal alloys traditionally used to cast frameworks for removable partial dentures (RPDs) were suggested as logical alternatives to gold alloys, and their use for post cores was advocated. A major disadvantage of base metal alloys was their hardness as these castings had to be ground and contoured at the chairside. Alternative alloys were later introduced to resolve the problems of contouring and finishing posts and cores fabricated from base metal alloys. Post cores made from silver-palladium alloys were more easily adjusted at the chairside and made suitable castings. Many properties of these silver-palladium alloys are similar to those of gold casting alloys, and they offer an economical and satisfactory alternative for custom-cast posts and cores (Morgano and Brackett, 1999).

2.3.2 Carbon fiber posts

In recent years, carbon-fiber materials have come into use for prosthodontic applications. The use of such materials for prefabricated posts offers a number of advantages, including biocompatibility, resistance to corrosion and fatigue, mechanical properties that closely match those of the tooth, and the option of easy removal of the post from the canal (Martinez-Insua *et al*, 1998).

The ParaPost FiberWhite® (Coltene, Whaledent) system has recently been introduced in South Africa with the claim by the manufacturer that the system will allow mechanical and chemical bonding to reinforce the tooth. The manufacturer also claims that the post with mono-directional fibers in a filled resin matrix has a Young's modulus approximating that of natural teeth, which should result in decreased stress concentration and therefore an increased longevity of the restoration. The colour of the post is white translucent, designed to minimize the shadowing under all-ceramic restorations. The parallel-sided posts are intended for passive seating in the canal, and the antirotational post head stabilizes the core material. The ParaPost FiberWhite® is available in four diameters and colour coded with matching drills.

Resin and resin fiber posts are easily retrievable when endodontic retreatment is necessary. The use of a Gates-Glidden drill through the existing post can act as a vertical guide for the drill, preventing the inadvertent instrumentation of the dentinal walls of the canal (Freedman, 2001). When the Glates-Glidden drill reaches the gutta percha, the process of endodontic re-treatment is routine. Once the canal is resealed, it is simple to rebond a new post in the canal. Post retrieval is therefore rapid, routine, and predictable. Cormier and co-workers (2001) compared the fracture resistance and failure mode of fiber, ceramic and conventional post systems at various stages of restoration. The fiber posts evaluated provided an advantage in that they were readily retrievable after failure, whereas the remaining post systems tested were non-retrievable.

The resin fiber post is similar in its characteristics to natural dentine when compared to any other previously used post. It has excellent transverse strength and acts as a shock absorber, dissipating much of the stresses placed on the finished restoration, while transmitting only a small fraction of these forces to the dentinal walls. The fiber posts bond to tooth structure and core materials via resin cements. It is delivered to the patient in a single-appointment, chair-side procedure and does not pose an aesthetic barrier to the final all-ceramic restoration.

Sidoli and co-workers (1997) showed carbon fiber posts to have inferior strength when subjected to forces simulating clinical behaviour and when compared to established metal posts. Stockton (1999) recommends the use of a carbon post system in cases where enough coronal and root dentine remains and where the artificial crown is well supported by the remaining tooth structure.

Although previous studies showed carbon fiber posts to have inferior strength, an earlier study by Love and Purton (1996) found the retention of carbon fiber posts to be similar to that of stainless steel prefabricated posts. The same study found serrated carbon fiber posts to be significantly less rigid than a similar-sized non-serrated carbon fiber post. Although less rigid, core retention to the serrated carbon fiber post was significantly better than the smooth post.

2.3.3 Glass fiber posts

The clear glass fiber, resin post (Luscent Anchor®, Dentatus, New York , NY) is designed to refract and transmit natural tooth colors for aesthetic post-and-core foundations. The Luscent Anchor® post is radiolucent, and identified on radiographs by surrounding resin cement. It is designed to be placed passively in prepared canals, it is available in three dimensions, and its size integrated with the Light Transmitting Posts (Dentatus, New York, NY). The Luscent Anchor® is easily removed, if required for endodontic retreatment.

Glass fiber posts have demonstrated similar clinical advantages to carbon-fiber posts. The primary advantage of glass-fiber posts is a modulus of elasticity (~40 GPa) that closely approximates that of dentine (~20 GPa). They are reported to enhance bond strength when used in combination with a wide variety of resin cements (Martelli, 2000). In addition to the aforementioned advantages, the Anchor Luscent System® (Dentatus USA, New York, NY) is characterized by a translucency that enables the transmission of light into the root canal, thereby allowing complete photo-polymerisation of the composite resin used to seat it.

2.3.4 Prefabricated Metal Posts

2.3.4.1 Alloys for prefabricated posts

Prefabricated posts have been manufactured primarily from nickel-chrome because of the considerable strength of these metals. In recent years, however, there has been a trend towards titanium and titanium alloys for posts. This is partly due to nickel sensitivity experienced by patients, mainly females. Nickel chrome posts are the strongest posts presently while pure titanium is said to be the weakest (Christensen, 1993; Smith *et al*, 1998). Titanium alloys are reported to be the most corrosion resistant (Smith *et al*, 1998). Titanium alloy posts usually containing small amounts of aluminium and vanadium, are intermediate in strength. Despite reports of breakage or bending of titanium or titanium alloy posts, these materials have shown to be successsful when used with: (1) adequate anti-rotational features in the remaining root (pins, channels), (2) strong build up material (composite or glass ionomer), and (3) a collar on the crown extended at least 1mm apically beyond the interface of the core and remaining root structure (Christensen, 1993).

2.4 Factors Affecting The Success Of Post Systems.

2.4.1 Post length

Various recommendations have been made which act as guidelines to determine adequate post lengths. Stockton (1999) listed the following guidelines:

1. The post should at least be equal to the incisocervical or occlusocervical dimension of the crown.
2. The post should be longer than the crown.
3. Post should be at least a third the length of the crown.
4. The post should be a certain fraction of the length of the root such as one half, two thirds, or four fifths.
5. The post should end halfway between the crestal bone and the root apex.
6. The post should be as long as possible without disturbing the root apex.

The length of the post has a significant effect on its retention and in most instances, the more deeply the post is placed, the more retentive it becomes. Shorter posts have been shown to have a much higher failure rate. Furthermore, posts should not disturb the apical seal. Leakage was reported to be considerably reduced when in excess of 4mm of gutta-percha remained in the apex of the canal. Another advantage to increased post length is a reduction in stress concentration (Hudis and Goldstein, 1986).

2.4.2 Post diameter

The remaining tooth structure following post preparation is important with regard to strength and resistance to root fracture. The desired post diameter is determined by tooth morphology to avoid removing too much tooth structure. Increasing the diameter of the post does not provide a significant increase in the retention of the post; but it can increase the stiffness of the post at the expense of the remaining dentine and the fracture resistance of the root. There is little indication for increasing the post width beyond the endodontic cleaning and shaping procedures for all post systems. The post diameter needs to be controlled to preserve the radicular dentine, reduce the potential for perforations, and permit the tooth to resist fracture.

2.4.3 Post Design

There are numerous prefabricated post systems available from dental suppliers that often create much confusion amongst clinicians. Stockton (1999), describes 6 basic commercial systems available:

1. *Tapered, smooth-sided posts*, such as Kerr Endopost *posts* (Kerr Manufcaturing Co., Romulus, Mich.).
2. *Parallel-sided, serrated, and vented posts,* such as Whaledent Parapost *posts* (Whaledent International, New York, NY.)
3. *Tapered, self-threaded posts*; for example Dentatus screws (Weisman Technology Internationl, Inc., New York, N.Y.).
4. *Parallel-sided, threaded, split-shank posts*, such as FlexiPost *posts* (Essential Dental Systems, S Hackensack, N.J.).
5. *Parallel-sided, threaded posts*; for example, Radix anchors (Maillefer/L.D. Caulk, Milford, Del.).
6. *Carbon-fiber posts*, such as C-post *posts* (Bisco Dental Products, Itasco, I11) or Composipost *posts* (RPT, Meylan, France) or ParaPost® Fiber White, (Coltène Whaledent).

Tapered posts are reported to produce the greatest stress at the coronal shoulder, and parallel posts generate the greatest stress at the apex of the canal preparation. Parallel-sided posts resist tensile, shear, and torquing forces better than tapered posts and distributes stress more uniformly along their length during function.

Sorenson and Martinoff (1984) studied 6000 endodontically treated teeth in general practice, comparing reinforcement methods, post length and manner of failure of these posts. Their results showed parallel-sided serrated posts to be the most successful clinical intra-coronal reinforcement when compared to tapered cast post and cores. Similar results were obtained when Isidor and Brøndum

(1992) compared tapered individually cast posts and cores to prefabricated parallel-sided posts and composite cores. Teeth with prefabricated posts and resin composite cores showed significantly higher resistance to intermittent loading than did teeth with tapered, individually cast post and cores.

In addition, parallel-sided posts were also shown to be more retentive than parallel-sided posts with tapered ends (Brown and Mitchem, 1987; Cooney *et al*, 1986; Sorenson and Engelman, 1990). The lack of retention seen with tapered-end posts is attributed to the lack of parallelism in the apical portion of the root.

Post design has been shown not to influence fracture resistance of endodontically treated teeth (Assif *et al*, 1993). The latter authors concluded that post selection should be based on a system that preserves tooth structure and possesses suitable retention of the core for restoration of the tooth.

2.4.4 Luting Agents

Luting agents, including zinc phosphate, polycarboxylate, glass ionomer, and filled and unfilled resin cements have been investigated extensively. The literature does not suggest any luting agent to be superior to another. Both zinc phosphate and glass ionomer cements are frequently used because of their ease of manipulation along with their history of success in luting procedures. Glass ionomer cement has been shown to have significantly higher retentive strength to dentine when compared to zinc phosphate cement (Young *et al*, 1985). However, other studies demonstrated no difference in retention of posts when comparing zinc phosphate, zinc polycarboxylate and glass ionomer cements (Chapman *et al*, 1985; Duncan and Pameijer, 1998). The use of filled and unfilled resins as luting agents has increased. However, they are technique sensitive because of their short working time and they are more adversely affected by improper root canal preparation than other cements.

Cohen and co-workers (1998) compared five different dental cements (resin composite [Flexi-Flow®, Essential Dental Systems], a glass ionomer [Ketac-Cem®, ESPE], two hybrid glass ionomers [Duet®, GC Corporation and Advance®, LD Caulk] using three different post systems. This *in vitro* study demonstrated that the resin cement had the highest overall mean retention of all the cements studied. Manufacturers of the newer glass fiber and carbon fiber posts recommend that resin cements be used for cementation and core build up.

The resin luting (dual-cured) cement exhibits high bond strength to tooth, metal and ceramic. It is easy to use and is predictable. Since it is dual-curing, the set can be initiated by the curing light, but light access is not required. Those areas not exposed to light will cure chemically within 4-5 minutes. Marginal areas that are exposed to the curing light will set within 20 to 40 seconds, minimizing the risk of moisture contamination. Christensen (1993) suggests resin cements be used when posts are not fitted tightly to post chambers in roots, preventing potential lateral post movement. Although resin cements appear to increase the retention of posts, it does not increase the tooth's resistance to fracture (Mendoza *et al*, 1997).

2.4.5 *Luting Method*

The actual method of cementing a post has been investigated, including placing the cement on the post and/or placing the cement in the canal with a lentulospiral, a paper point, and an endodontic explorer. None of these methods proved to be superior to the other. Linde (1993) suggests that the threaded posts may aid in the distribution of luting cements, allowing it to flow through through the screw threads. This may improve the retention of the post provided that there is optimal fit of the post to the reamed canal.

2.4.6 *Canal Shape*

The predominant canal shape is ovoid and the walls of prefabricated posts are commonly parallel. Stockton (1999) therefore suggests that the majority of luted prefabricated posts are unlikely to adapt well along the entire interface with the canal walls. A post that does not fit well, whether due to an inappropriate natural shape or ill-considered overpreparation, will result in decreased retention of the prosthetic restoration and, possibly, fracture of the remaining dentinal structure.

2.4.7 *Preparation of the canal space and tooth*

Methods of preparing the post space include rotary instruments, heated instruments and various solvents. No method has been found to be superior to the other. However, researchers agree that a minimum of 4-5mm of gutta percha must remain to preserve the apical seal. Following gutta-percha removal (using Peeso reamers or Gates-Glidden burs), root canal reamers can be used to widen the canal space by a reaming action to ensure a relatively round preparation. Most prefabricated post systems have twist drills to shape the canal following hand instrumentation. Twist drills should not be used to remove gutta-percha. They should also not be forced, but allowed to passively follow the course of the canal space created. Stops may be placed on engine-mounted drills at the desired depth as an added precaution. Newer post systems have depth markers on their twist drills that facilitate easy measurement of the canal depth.

Drills should be used with caution as they can cause undesirable angulation and perforation of the root. The guide for post preparation is to use the smallest possible canal diameter to preserve the inherent strength of the root (Stockton, 1999).

Wu and co-workers (1998) evaluated the leakage along apical root fillings remaining after post space preparation and cemented posts in root canals. An interesting finding was that the remaining apical 4mm of root filling was shown to leak statistically significantly more than the original full-length root canal filling. However, this leakage created by removal of the coronal part of the root filling may be compensated for by the cemented posts.

2.4.8 *The ferrule effect*

Isidor and co-workers (1999) evaluated the influence of post and ferrule length on the resistance to cyclic (fatigue) loading of teeth with prefabricated titanium posts (ParaPost) and crowns. This was an *in vitro* study done on bovine teeth where the ferrule design was prepared at adequate height and ideal finish lines. Their results showed that ferrule length was more important than post length in increasing the fracture resistance to cyclic loading of crowned teeth. This was in accordance with previous studies (Milot and Stein, 1992) that showed bevelled preparations to provide a significant increase in resistance to root fracture.

However, in the compromised root canal the residual dentine is often inadequate to place a ferrule design. Saupe and co-workers (1996) showed that when a bonded resin reinforcement and post cementation was used on structurally weakened roots, there was no statistically significant difference between post and core restorations that used a ferrule and those without a ferrule. The use of a ferrule, under weakened structural conditions, was found to provide no additional benefit for retention and resistance to fracture and only necessitates additional loss of tooth structure.

2.4.9 *Core design*

The ability of a core reconstruction to withstand compressive forces and micromovement are primary factors in the prognosis of a coronal restoration.

There are numerous components that play a key role in stabilizing and retaining an artificial crown. These include core material and bonding agents. The design of the coronal portion of the core is often determined by caries, endodontic access, or tooth fracture. If sufficient sound dentine remains, this tooth structure can be retained and incorporated into the core. Hudis and Goldstein (1986) reported that preparations with residual coronal structure had more evenly distributed stress concentrations.

Numerous materials have been used for the core materials including amalgam, glass ionomer and resin composites. Amalgam represents one of the most widely used clinically effective core materials. Cores fabricated with amalgam demonstrate statistically higher fatigue resistance when compared to composites and glass ionomers (Gateau *et al*, 1999). However, amalgam is not reliable as a core build-up material when there is a lack of bulk. Setting time of amalgam alloys to reach maximum hardness can limit the ability to prepare the tooth in the same appointment, especially when using admixed, high copper amalgams.

The glass ionomer materials have favourable characteristics: a weak bond to enamel and dentine; fluoride release; and a low coefficient of thermal expansion. Disadvantages of glass ionomer materials for use as core materials (including the silver-filled glass ionomer materials) include lack of strength to withstand masticatory forces and brittle characteristics (Cohen *et al*, 1994; Cohen *et al*, 1997; Gateau *et al*, 1999).

Resin composite materials are also extensively used for crown procedures. Resin composites offer several advantages including acceptable strength, adherence to tooth structure, ease of manipulation and rapid setting time as compared to dental amalgam. These properties enable the clinician to complete the core immediately after the placement of the prefabricated post. However, the dentine may suffer from microleakage and the ability of composites to absorb moisture make their dimensional stability unsatisfactory (Gateau, 1999).

The composite core has excellent adaptation to the remaining tooth structure. Since it involves a direct, chairside procedure, it is simple and predictable. The composite core forms strong bonds to remaining tooth structure, bondable posts, resin cements, and ultimately, the final restoration. Composite resin is easy to prepare to an ideal foundation for the final restoration, and it is available in a variety of colors for maximum aesthetic benefit.

Cohen and co-workers (1994) evaluated the fracture load for three different core materials (a titanium reinforced resin composite, an amalgam and silver-reinforced glass ionomer). Their study showed the resin composite (TiCore®) core to have greater fracture resistance values than amalgam (Tytin®) and silver-reinforced glass ionomer (Ketac Silver®).

The post-and-core materials should also be compatible. Currently clinicians are placing many all-ceramic restorations, crowns, onlays, and veneers, often with supragingival margins. A metallic or dark post and core will be readily visible through these semi-translucent restorations. This is an aesthetic compromise that most patients will not accept. The ideal core shade should be somewhat yellowish, resembling the dentine it is intended to replace. The yellowish tint being faintly visible through the all-ceramic restoration will provide a natural appearance to the restored tooth.

Cohen and co-workers (1999) demonstrated that the use of a bonding agent increased the resistance of composite cores to torsional forces. Lack of a bonding agent dramatically reduced the resistance to torque.

2.6 Biomechanical considerations in restoring endodontically treated teeth

Dentine provides a solid base for the restoration of a tooth. The structural strength of a tooth depends on the quantity and inherent strength of dentine and the integrity of its anatomic form. After endodontic therapy there is an appreciable loss of dentine including anatomic structures, cuspal ridges, and the arched roof of the pulpal chamber. This results from restorative procedures that rarely preserve dentine. According to Assif and Gorfil (1994), the fundamental problem is the quality and quantity of healthy dentine remaining to retain the restoration.

Many dental clinicians believe that endodontically treated teeth are weakened and more prone to fracture because of desiccation or premature loss of fluids supplied by vital pulps. This assumption is based on research that has shown pulpless teeth to have approximately 10% less collagen-bound water. In addition, as more tooth structure is removed, the resistance to occlusal forces is diminished and the possibility of fracture increased. Assif and Gorfil (1994) reported on studies that demonstrated canal preparation to weaken the root and decrease its ability to withstand forces before insertion of a metal post. The maxillary anterior teeth are more vulnerable as they are more exposed to labially directed forces. One millimetre of remaining buccal dentine wall was shown to be more prone to fracture under horizontal impact compared to buccal dentine walls that had 2 or 3mm of buccal dentine walls remaining (Tjan and Whang, 1985). Therefore a sufficient buccal dentine wall must be conserved in maxillary anterior teeth because of its function as a fulcrum toward horizontally directed forces.

Cracks or fractures of roots frequently occur after endodontic treatment, especially in those teeth "reinforced" by posts. Many researchers have attempted to qualify and quantify the stress distribution within the root during different stages of restorative procedures with conflicting results (Assif and Gorfil, 1994; Ko *et al*, 1992; Mentik *et al*, 1998; Milot and Stein, 1992).

Ko and co-workers (1992) developed plane strain and stress finite element models in order to provide some insight into the role of posts in reinforcing pulpless teeth. Finite element analysis is described as a powerful and popular numerical method in stress analysis and has been applied in dental mechanics for nearly two decades. In the latter study, three loading forces were applied to these models: (1) a masticatory force at 45 degrees lingual to the incisal edge, (2) a traumatic force which acted horizontally at the labial crown and (3), a vertical force acting at the incisal edge. Under masticatory loads, the maximal tensile stresses were concentrated on the lingual side. With post placement, dentine stresses were reduced substantially while the post was stressed significantly. The reductions in peak dentine stress reached 30 percent. Similar results were observed with traumatic loading, although greater loading values were recorded. When a vertical force was applied (as in posterior teeth), dentine stresses were concentrated around the apex of the post and were reduced drastically in other parts of the dentine. This reduction is because the posts are under compressive force in vertical loading. The authors concluded that because incisors and canines are rarely subjected to vertical loading, the reinforcement effects of posts are doubtful in these teeth. The drawbacks of this study are that the models used were mainly two-dimensional in nature and could not completely simulate actual teeth. In addition, these rather complex analyses did not describe relationships between the geometry of the posts and stress distribution.

The effect of specific geometric features of the post on the distribution and severity of the stress generated was investigated by Mentik and co-workers (1998). A photo-elastic material with elastic properties comparable to dentine was used and overall stress patterns examined using polarized light. Seven geometrically distinct posts were compared in terms of stress generated at various stages of insertion. Mild to moderate stresses were recorded for all posts during the shaping of the canal and fitting of the post. During cementation, the pressure exerted by the cement on the post is considered to be distributed equally along the length of the channel. The severity of the residual stress and its distribution, however, differed from system to system. Immediately after cementation a quarter counter rotation reduced stresses in the apical region. An interesting finding was that a post with no head, produced no coronal stresses. Systems with small heads were shown to have mild to moderate coronal stresses. In contrast, systems with larger heads (of at least $3mm^2$) were found to have limited or no coronal stress. The authors concluded that with respect to coronal stress, it would appear to be better for a post system to have no head at all than having a head that is too small. As may be expected, stress was also found within the material along the threaded part of the posts. The severity of the stress increased with an increase in the pitch of the thread.

Assif and Gorfil (1996) have a somewhat contradictory theory and believe that posts do not noticeably reduce forces at the margins of a crown nor do they cause a more equal distribution or dispersion of forces along the length of the root. Their arguments are based purely on the biomechanical properties of a tooth. They describe tapered posts to exhibit more favourable stress concentrations. Cylindrical posts are said to exert compressive forces on the root apical to the sharp angles and can create dentinal cracks from the tip of the post to the circumference of the root. The preparation of the canal for this post leaves a thin dentinal wall at the apex of the preparation, where concentration of forces is greatest, and also increases the risk of perforation. Tapered posts exhibit a lower concentration of stress in the apical portion, probably because of the absence of sharp line angles and conservation of tooth structures in this area.

Lateral forces result in high stress concentration in radicular dentine at the coronal one third of the root. The rotational axis is said to be located at the crest of the alveolar bone and the forces are greatest on the circumference of the root, whereas the concentration of the forces is lowest within the root canal. The center of the root or canal is a neutral area with regard to force concentration. This force distribution explains the susceptibility of teeth to fracture at the cemento-enamel junction when lateral forces are exerted on the coronal portion of the tooth. The contribution of the post inserted in the root canal or area of zero forces is negligible because the post absorbs minimal forces in this position (Assif and Gorfil, 1994).

The distribution of forces questions the value of intra-radicular posts and identifies the need to introduce techniques that strengthen the external surface of the root. The thickness of the dentinal wall at the root circumference is critical, and there is a direct correlation between the root diameter and the ability of the tooth to resist lateral forces and avoid fracture. Conservation of dentine is mandatory, and restorations that support this concept are preferable.

2.7 The Structurally Compromised Root Canal

2.7.1 Intraradicular Rehabilitation

Numerous studies have questioned the concept of an endodontic post reinforcing or strengthening the tooth structure (Assif and Gorfil, 1994; Ko *et al*, 1992). The incorporation of a post has often shown to further weaken the tooth. Ideally, the post should provide retention, but without inducing undue functional stresses. As mentioned before, the post space is often compromised due to the loss of significant amounts of coronal and radicular tooth structure as a result of caries, complex restorations, endodontic retreatment and/ or fracture. The most popular post used for these mostly flared canals was the cast post. This wide inflexible post design created wedging effects along the root surface and greatly increased the risk of root fracture.

The introduction of materials capable of bonding to dentinal structure has created an opportunity to reconstruct and rehabilitate lost dentinal tissues to save severely damaged teeth. When the weakened root is internally rebuilt with suitable adhesive dental materials, the root is dimensionally and structurally reinforced to support and retain a post and core for continued function of the tooth. Lui (1994a) introduced an intraradicular composite reinforcing technique in conjunction with the re-establishment of matching post canal spaces. This technique has allowed compromised, root-filled teeth to be restored with functional, aesthetic ceramo-metal restorations.

Clinicians have taken the initiative to rebuild lost tooth structure and as such minimizing existing flaring of the root canal structure with great success (Lui, 1984; Dickerson, 1994; Linde, 1993). The rationale for the use of dentine-bonded composite for intra-radicular rehabilitation is well established.

The thickness of composite that is bonded between the metal post and dentinal surface will decrease the dark discoloration that may show through the labial aspect of the root through the thin labial tissues. The use of titanium alloy or other noble metal posts will further limit discoloring oxidation. This is especially important for the anterior region, where aeshetics is often of great concern.

An intraradicular rehabiliatation that is matrixed within the dentine is less likely to be subjected to microleakage, due to the advantages of bonding over cementing (Freedman *et al*, 1994). The inherent problem with light-cured dentine-bonded composites is the inability of the light to penetrate to a depth greater than 5mm to 6mm. Until recently, it has been impossible to transmit light down the length of the canal and this posed a particular problem in restoring the intraradicular space. The introduction of light transmitting posts enabled the clinician to complete polymerisation of a light cured or dual cured composite resin along the length and circumference of a prepared post channel.

<u>2.7.1.1 Clinical technique</u>

The technique involves the use of light-transmitting posts (Luminex, Weisman Technology) that allows the transmission of light into the root canal to polymerise any composite resin placed within it. The Luminex Light Transmitting Post System (Dentatus, New York, NY) has matching smooth plastic impression posts, matching grooved burnout casting posts, matching prefabricated titanium, stainless steel, and gold-plated metal posts, as well as reamers and retentive groove cutters.

The compromised obturated root canal is prepared with suitable reamers to the desired size and depth to receive a corresponding-sized light-transmitting plastic post carrying a depth-marking ring. The matched post is removed and the internal root dentine is acid etched, rinsed and dried. To bond the composite resin to dentine, a dentinal bonding system is used according to the manufacturer's instructions. The dentinal primer is applied with a brush over the dentinal surfaces and dried with oil-free air. The adhesive is then similarly applied over the primed dentine. After the light-transmitting post is inserted, the adhesive is cured for 10 seconds with a suitable light-curing unit. The light-transmitting post is again removed.

For reconstituting and rehabilitating the root, a visible light-curing hybrid composite (e.g. Lui[1999] used Prisma TPH by Caulk/Dentsply) is selected. To facilitate its placement into the depths of the root canal, the composite resin is dispensed into the bonded canal with a nozzle. Suitable plastic instruments are used to pack the composite resin into the canal. The light-transmitting post is reseated to its full depth into the uncured composite to ensure the desired post canal length is achieved. Following removal of excess material from the coronal root face, a light-curing unit is applied to the end of the plastic post to transilluminate light along its entire length to polymerize the surrounding composite resin. The post is then removed with a hemostat, leaving a reinforced root with a patent, size-matched post canal.

At this stage the post space can be treated routinely. Lui (1994) recommends several options to restore the damaged tooth for function and aesthetics. Should a cast post be desired, an anti-rotational cavity can be prepared on the root face, and matching plastic posts can be used with either the direct or indirect technique to obtain the post and core pattern. Alternatively, any prefabricated matched post of choice (e.g., metal post, resin fiber or glass fiber post) can be cemented into the prepared canal and a composite resin core can be built up.

2.7.2 A summary of resin composites

The advantages of bonded resin composite restorations include conservation of sound tooth structure, reduction of microleakage, prevention of post-operative sensitivity, marginal staining and recurrent caries, transmission and distribution of functional stress across the bonding interface to the tooth. Bonded restorations also offer the potential for tooth reinforcement (deteriorated restorations can be repaired with minimal or no additional loss of tooth material), cosmetic restoration and recontouring of teeth with little or no preparation, and diminished need for the use of liners and bases (Fortin and Vargis, 2000).

2.7.2.1 Composite based resins

A composite is defined by Fortin and Vargas (2000) as a material that consists of two or more components. Typically, a dental resin composite contains an organic binder and an inorganic filler incorporated into a system that would induce polymerisation. The filler particles are coated with a coupling agent to bond to the resin matrix. Change of size and filler-loading has improved the wear resistance of the early composite resins. Modern composites contain filler such as quartz, colloidal silica, silica glass containing barium, strontium and others. This filler increases the strength and modulus of elasticity and reduces the polymerisation shrinkage, the coefficient of thermal expansion, and the water sorption.

A major drawback of current composite-based resins is that they contract or shrink during conversion from monomer to polymer. The resin matrix of all composite-based resin restorative materials shrink volumetrically approximately 10 percent during polymerisation. The polymerisation stresses the adhesive between the tooth and the restorative material, frequently resulting in failure of this bond. However, shrinkage is markedly reduced by the incorporation of filler particles and, therefore, the higher the filler loading, the less shrinkage should take place (Fortin and Vargas, 2000).

Resin composites are often classified according to particle size, that is:

- macrofilled – more than 10μm and up to 100μm;
- midsized filled – less than 10μm and more than 1μm;
- minifilled – less than 1 and more than 0.1μm;
- microfilled – less than 0.1μm.

Commonly, composite-based resins are frequently referred to as hybrids. A hybrid resin is a composite in which at least seven to 15+ percent microfiller of fumed silica has been added to the mixture. Hybrids incorporate fumed silica to help with the handling properties.

Composite-based resins also have a range of translucency and opacity that reflects that of enamel and dentine. Barium is the element that is most commonly incorporated into composite-based resins to increase radiopacity.

2.7.2.2 Polymerisation

The polymerisation shrinkage of resin composite represents a problem in operative dentistry because it may lead to gap formation between the resin composite restorative material and the cavity walls. Such gap formation may compromise the restoration because it entails microleakage, staining, bacterial invasion and recurrent caries. To produce and maintain a leakproof restoration, strong and durable bonds between the resin composite and the tooth structures must be established to neutralize the contraction stress.

Acid etching of enamel greatly increases the retention of resin to enamel. The bonding is micromechanical, as the resins form tag-like extensions into the etched enamel surface. Dentine, however, is a less favourable substrate than enamel for resin bonding. Many factors contribute to this: the high organic content of the dentine, the presence of fluid, the odontoblastic processes in the dentinal tubules, and the presence of a smear layer on prepared surfaces.

Studies have been conducted to evaluate the bond strength of resin composite to enamel and dentine by using different bonding agents. Many new dentine bonding agents produce definite improvements in tensile and shear bond strength. Leirskar and co-workers (1998) evaluated the shear bond strength of five different dentine-bonding agents (All-Bond 2, Optibond, Prisma Universal Bond, ScotchBond Multipurpose and Syntac) in combination with two resin composites (Tetric® and Z100®). Their results showed that the bond strength of dentine bonding agents may depend on the choice of restorative material. The *in vivo* bond strengths of these bonding agents differed significantly and were even found to exceed the cohesive strength of dentine. The authors suggested that the correct combination of resin composite and dentine adhesive agent be used as recommended by the manufacturer.

Restorative resin composites can be either chemically or light activated. The mode of cure for these two types of resins is different and was hypothesized to influence the flow capacity of the resin. Light-cured resin composites undergo an immediate and rapid polymerisation reaction that permits less resin flow than chemically cured resin composites, because they do not exist in a gel stage for very long. Theoretically, the lower the capacity to flow, the greater will be the contraction stress, which significantly affects the success of the adhesive bonding procedure. In fact, it has been reported that light-cured resin composites generate higher polymerisation shrinkage stresses than the analogous chemically cured composites (Carvalho *et al*, 1996).

2.7.3 Composite polymerisation in flared canals

Research has demonstrated that composite reinforcement strengthens damaged and weakened teeth, allowing them to be rehabilitated (Lui 1994a; Saupe, 1996). However, the use of auto-curing composite may pose a particular problem during placement into a flared root canal, as it is difficult to control the rapidly polymerising composite. The light-curing composites have better handling characteristics, as they allow sufficient time and control for proper placement into the canal. However, complete polymerisation cannot be guaranteed, especially when the composite is placed deeper than 4-5mm. This is due to the limited transmission of light through the bulk of the intra-radicularly placed composite.

Lui (1994b) studied the depth of composite polymerisation within simulated root canals using light-transmitting posts. He reported that the depth of cure of the composite was significantly increased with the use of a light-transmitting post. The larger the diameter of the post used, the greater the depth of cure. Light-transmitting posts were shown to achieve a depth of cure exceeding 11mm (Lui, 1994b, Anooshiravani and Nathanson, 1996; Strassler *et al*, 1997).

2.8 CONCLUSION

The rationale for placing posts has shifted in the last two decades, from efforts to strengthen roots to provision of retention and resistance to displacement of core materials. In teeth with significant loss of tooth structure, it has become important to assess alternatives to morphologic post rehabilitation.

The alternative of using a dentine-bonding composite resin for intra-radicular reinforcement has shown to provide good clinical results (Godder *et al*, 1994, Lui 1994a; Freedman, 1994; Trushkowsky, 1995). The fracture resistance of the roots was significantly improved with a resin reinforced post and core system compared to a conventional morphologic cast post. Furthermore, research has shown that a ferrule design is of less importance and does not affect fracture resistance in compromised teeth (Saupe *et al*, 1996).

The actual type of post does not influence the fracture resistance of endodontically treated teeth in the ideal clinical situation, where most of the tooth structure can be preserved (Assif *et al*, 1993; Milto and Stein, 1992). However, the ideal post system for compromised teeth has not been reported on previously. This *in vitro* study would attempt to examine the effect of different post systems on the fracture resistance of compromised roots.

2.9 Null Hypothesis

The null hypothesis for this study is that there is no significant difference with regard to fracture resistance among the four post systems used for the rehabilitation of the flared canal.

2.10 Aims & Objectives

Martelli (2000) writes that the success of the endodontic post should not be evaluated in terms of its size or rigidity; instead, the post should be measured by its ability to respect the root structure, optimise the bond between the various components (e.g., dentine, composite resin, post and core), and be able to function as a cohesive unit.

The purpose of this *in vitro* study is to investigate the fracture resistance of structurally compromised teeth using four dynamically different post and core systems in the rehabilitation process.

CHAPTER THREE: RESEARCH DESIGN AND METHODS

3.1 Sample Selection

One hundred intact maxillary incisor roots with similar length and dimensions were selected for this study. The teeth were kept in saline under humid conditions throughout the duration of the study.

3.2 Tooth preparation (Appendix 1)

The crowns of the selected teeth were sectioned perpendicular to the root axis, leaving approximately 2mm above the cemento-enamel junction (CEJ). The root canal of each tooth was instrumented with a conventional step-back technique to an International Standardization Organization (ISO) file size of 35 at the apical constriction. Canals were irrigated with 2.5% sodium hypochlorite solution throughout preparation and dried with paper points. Each canal was obturated by lateral condensation with gutta percha points against an ISO 35 primary gutta percha cone. AH26® (DeTrey/Dentsply) root canal cement, which contains no eugenol, was used as the sealer. Gutta percha was subsequently removed from each canal leaving 4mm of material as a hermetic seal at the apex.

To simulate extensive clinical structural damage, the canal space of each root was then further prepared by routing out the internal dentine, leaving specimens with an 8mm length of post space length and a residual dentinal wall thickness of 1.0

mm to 1.5mm at the CEJ. The buccal aspect of the residual root at 0.5 and 5.0mm below the incisal surface will be measured for uniformity in thickness (1.0 mm to 1.5 mm) among the specimens. Additional measurements of each root were taken namely: root length, circumference at the CEJ, bucco-lingual and mesio-distal dimensions.

The one hundred specimens were then randomly divided into four groups of 25 teeth each as follow (Fig.1):

Group A: morphologic cast post and core

Group B: resin reinforced glass-fibre post

Group C: resin reinforced carbon fibre post

Group D: resin reinforced prefabricated parallel-sided titanium post

3.3 Canal preparation *(Appendix 1)*

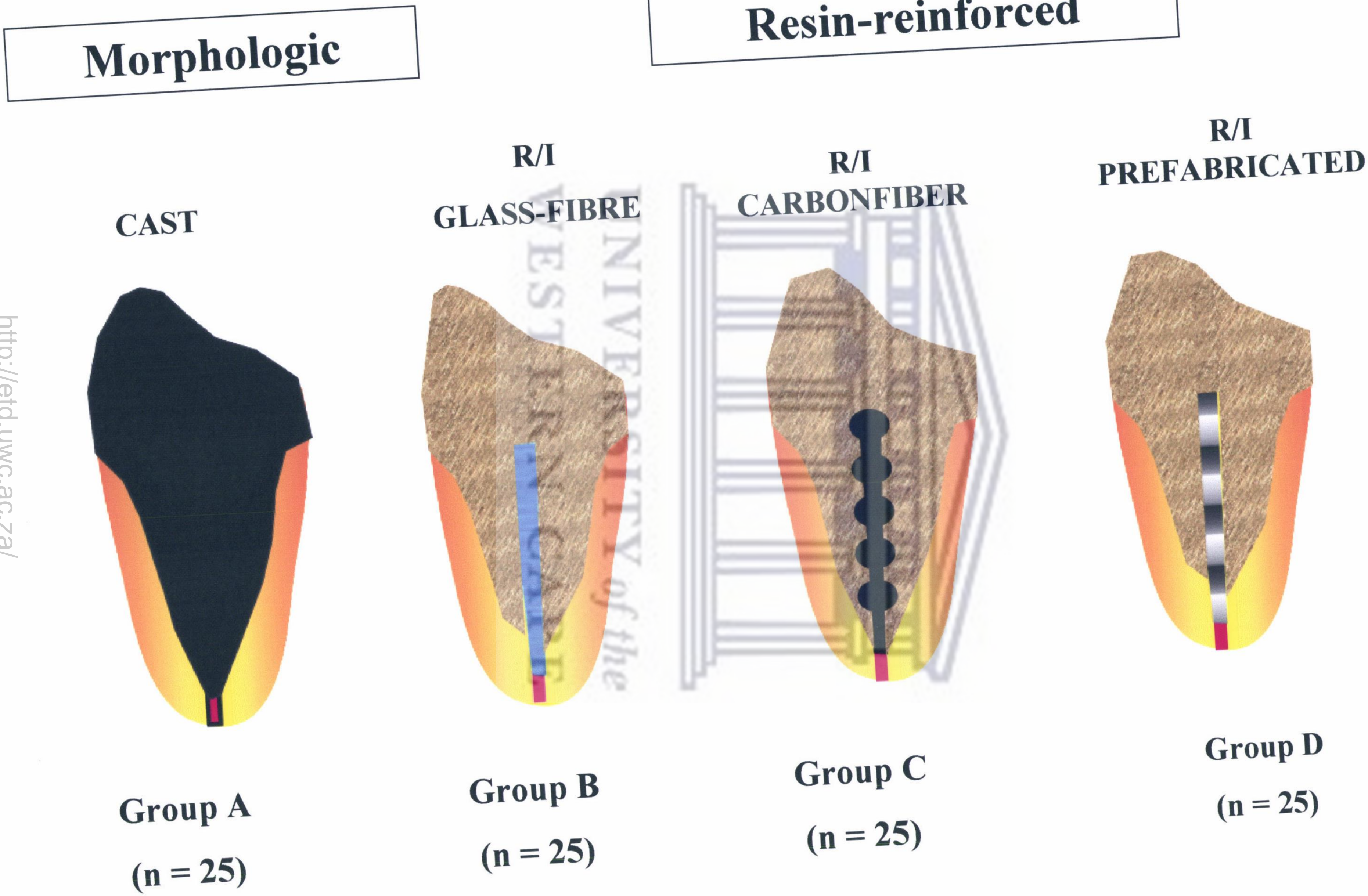
Morphologic group (Group A)

The custom (morphologic) post and core was used as a control because of its wide acceptance as a means of restoring thin-walled, endodontically treated teeth. Acrylic patterns (Duralay®) were made for all specimens with this group and then cast.

Resin-reinforced group (Groups B. C and D)

Apart from Group A, root canal spaces of all specimens were prepared by etching the surface with 37% phosphoric acid for 15 seconds followed by rinsing with water for 30 seconds and air drying. Prime & Bond 2.0® (Caulk/Dentsply) was placed according to the manufacturer's directions.

Figure1: Sample Groups



3.4 Canal rehabilitation *(Appendix 2)*

Resin-reinforced group (Groups B. C and D)

Visible light cured TPH® composite (Caulk/Dentsply) was injected into the canal space and vertically condensed using a flat plastic. A 1.4mm diameter light-transmitting post (Luminex®, Dentatus) was then inserted and centered in the canal space. The resin was light-cured through the post for 1 minute and another 20 seconds following the removal of the light-transmitting post.

Matching diameter glass fibre posts (Anchor Lucent®), carbon fibre posts (FiberWhite®) and titanium parallel-sided posts (Classic Dentatus Posts®) were passively cemented with auto-curing resin cement (ParaPost Cement®, Whaledent) respectively in Groups B, C and D. The core was then built up using visible light cured TPH® composite (Caulk/Dentsply).

3.5 Final restorations *(Appendix 3)*

All cast posts (Group A) were produced in a non-precious metal alloy (Wiron[99], Bego Germany) and air abraded with 50μm silica particles. These cast posts were cemented with auto-curing resin crown-and-bridge cement (ParaPost Cement®, Whaledent).

The core build-up for the remaining groups was done using TPH® (Dentsply/ Caulk). The core conformed to the overall shape of the root and the height was standardized to approximately 8mm. The point of load application was standardized by the inclusion of a small mark (using a diamond bur) on the palatal aspect of the composite core.

3.6 Fracture Testing *(Appendix 3)*

The root of each restored tooth was embedded in an acrylic block so that 3mm of natural root structure was exposed. The specimens were randomly chosen for transverse loading in a universal testing device (Zwick, Model 1446). The machine applied a load against a predesigned indentation on the lingual aspect of the core build-up. This would be at an angle of 130 degrees to the long axis of the tooth (Fig.2, Appendix 3).

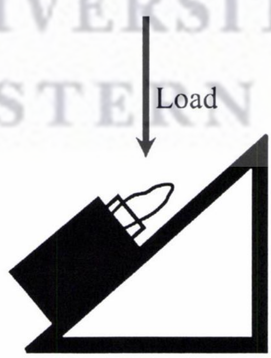


Figure 2.

This angle of loading was chosen to simulate a contact angle found in Class I occlusions between maxillary and mandibular anterior teeth. Transverse loading was maintained under a constant crosshead speed of 0.5 mm /min until failure resulted, as measured by a sudden release of load on the specimen. All samples were loaded until failure. The failure threshold was defined as the maximum load a sample could withstand. The failure load values were captured and recorded by a test program (TestXpert, V 7.1) that was directly linked to the universal testing machine. The load at fracture was recorded and the fracture mode identified. A record was kept of fracture lines on the coronal portion of the fractured root with a bisecting microcope at a magnification of 25 times.

3.7 Data Analysis

The data was analysed using nonparametric tests. The group medians were compared using the Kruskal Wallis Test for ranked data. All analyses were done using Microsoft® Excell 2000 software package.

4.1 Tooth Dimensions

The root sizes (relative to root length, circumference and mesiodistal and bucco-lingual widths of the roots), means and standard deviations of failure loads are listed in Table.1 (see raw data, Appendix 4).

Table 1. Mean Failure Loads

	Cast post	**Glass Fiber Posts**	**Carbon Fiber**	**Titanium**	**Average**
Tooth dimensions (mm):					
Average BL	6.71	6.37	6.30	6.51	6.47
Average MD	5.62	5.35	5.25	5.24	5.37
Average Circum	20.08	19.68	19.76	19.84	19.84
Average Root Length	16.00	16.08	16.12	15.62	15.96
Fracture Loads:					
Mean	1673.41	678.84	653.01	682.82	922.02
Median	1859.22	645.61	651.11	659.10	
SD	490.74	199.45	199.94	208.86	527.75
Range	1438.45	842.64	1030.99	849.44	
Min.	672.55	223.82	169.60	346.41	169.60
Max.	2111	1066.46	1200.59	1195.85	2111.00

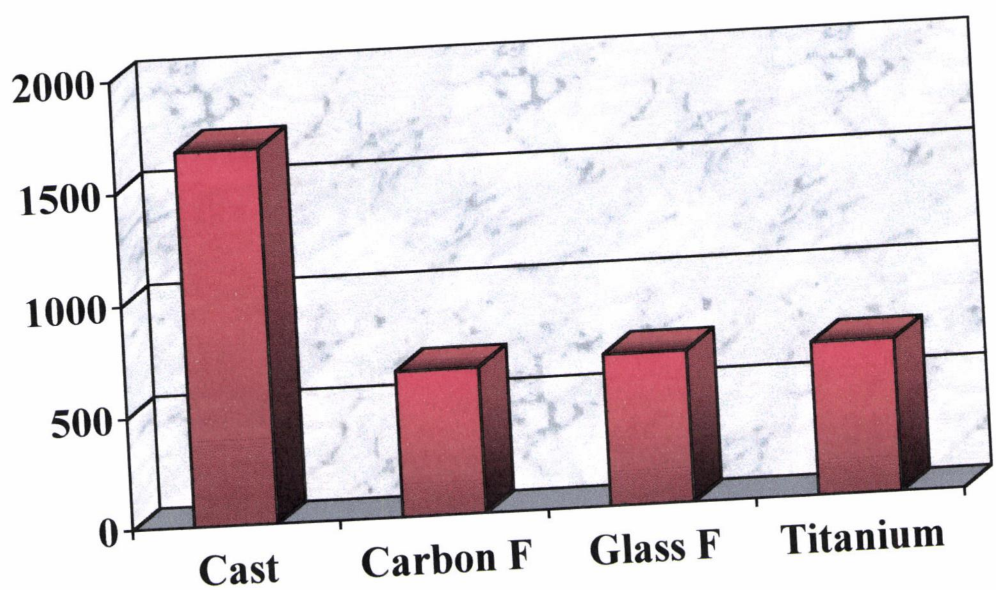
SD = Standard Deviation; BL = Bucco-lingual; MD = Mesio-distal; Circum = Circumference

The average bucco-lingual and mesio-distal widths of the roots of the total number of specimens (n = 100) were 6.47mm and 5.37 respectively. The average circumference was 19.84mm and the average root length was 15.96mm. When the 4 groups were compared with regard to their bucco-lingual widths, root lengths and circumference, no significant difference was found amongst the four groups. However, a difference was found in the mesiodistal widths of the cast group as compared to the other 3 groups. A weak correlation was found between tooth circumference and mean fracture load.

4.2 Fracture Loads

All samples experienced a peak load and then, for most, the load would fall gradually and spasmodically until catastrophic failure occurred. The failure load recorded was the peak load. The mean failure loads are illustrated in Figure 3 (see appendix 5).

Fig. 3. Mean Failure Loads (N)



The difference in fracture resistance between the morphologic (cast) and the reinforced group was statistically significant for these compromised roots (Kruskal Wallis Test, $P = 0$) (Table 2).

Table 2. Summary of the Kruskal Wallis Tests

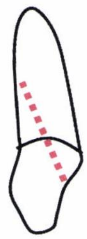
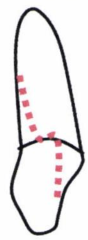
Post (n = 25)	**RankSum**
Cast	984.5
Glassfiber	214.0 *Tests Statistic H =48.985*
Carbonfiber	919.5 *P- value = 0*
Titanium	1006

The difference in fracture resistance between the three reinforced groups was found not to be significant ($p > 0$).

4.3 Fracture Modes

When the mode of failure was quantified, the large majority of failures occurred by root fracture (81%). As this study was designed to simulate structurally weakened teeth, the high percentage of fractured roots at failure was an expected outcome. The fractures in all samples occurred opposite the area where the fracture load was applied.

Table 3. Failure Modes and Distribution

Fracture pattern	 A	 B	 C	 D	
Cast			25		25
CF	12	10		3	25
GF	8	12		5	25
Ti	8	6	1	10	25
Total (%)	28	28	26	18	100

FW= CarbonFiber; GF = GlassFiber; Ti = Titanium

Oblique fractures through the central core of the occlusal surface (through the cingulum area) were generally observed for the reinforced group. Both the reinforced and cast group showed a specific pattern of fracturing (Table 3). In the reinforced group, a main fracture line started in the cingulum area and proceeded through the composite core alongside the post, and fracturing the outer dentine as well. When a load was applied to the cast group, the first breakage occurred at the cement-dentine occlusal interface, fracturing the root bilaterally on the proximal sides (fracture pattern C). The fractures of the cast posts were observed to be more destructive and often splintering the roots into many fragments.

Following destruction, each specimen was radiographed to evaluate the integrity of the post. Radiographic examination revealed no visible fractures of any of the posts (morhophologic and reinforced groups).

CHAPTER FIVE: DISCUSSION

In this *in vitro* study, teeth were randomly selected and divided into 4 groups. Although most of the tooth dimension data showed an equal distribution among the 4 groups, the mesio-distal widths showed a somewhat skewed distribution (Kruskal Wallis, $Z > 1.96$). Variations among specimens (within a sample group) are expected because of the natural anatomical variation among the teeth.

Attempts were made to standardize the core shape, but proved to be inappropriate taking into consideration the variation in the tooth circumference. The cores were built up using TPH® (Dentsply/ Caulk) to an average height of 8mm. A cast post-core or prefabricated post and composite core alone is not a complete restorative technique. However, the coronal portion of the cast post and cores and composite cores covered the cervical margins of the roots achieving a full crown effect.

The importance of maintaining tooth structure bulk to reduce tooth fracture has been well-documented in the literature (Guzy and Nicholls, 1979; Milot and Stein, 1992; Sorenson and Martinoff, 1984). This study, however, was designed to utilize structurally weakened roots with minimal remaining dentinal thickness. The residual dentine walls were all standardized to a width of 1 to 1.5mm using calipers to measure at frequent intervals during post space preparation. The width was chosen to simulate extensive tooth damage (in the clinical situation often due to caries, endodontic re-treatments,etc). The significance of the amount of remaining buccal dentine wall of the post channel in resisting horizontally directed loads was previously investigated (Tjan and Whang, 1985). The latter study compared the fracture resistance of roots (with gold posts) with 1mm, 2mm and 3mm residual dentine walls. The post spaces with 1mm remaining buccal dentine walls were more prone to fracture under horizontal impact than those that had 2 or 3mm of remaining buccal dentine walls. A high fracture rate was therefore expected in this *in vitro* study.

A morphologic cast post (Group A) was used as the control group as this has been the conventional and widely accepted method of restoring the flared canal. However, when using these cast posts, it was difficult to achieve an intimate fit in the canal (Freedman *et al*, 1994). In the remaining 3 resin reinforced groups, light cured composite was bonded to the dentine walls with a dentine bonding resin. The composite ordinarily would not cure in the depth of the canal because light from the curing unit would not be able to penetrate it. In this study, a clear plastic post (Luminex® Light Transmitting Post, Dentatus) was used to transmit light down the center of the canal to photo-activate the polymerization process. The plastic post was removed and a matching size post was bonded to the composite with auto-curing resin cement (ParaPost®). The posts were well adapted to the composite, which was well adapted to the dentine wall of the flared canal.

The first phase of rehabilitation of a flared canal with composite resin is a substantial improvement over the use of a single stage cementation technique. Composite resins can be bonded to the internal aspect of the root canal space with dentine bonding agents, whereas traditional cements bond mechanically to tooth structure and do not allow a chemical bond to form. Therefore, while cements have no chemical activity with either tooth or restorative surfaces, composites can be bonded to enamel, dentine, metal, and ceramics. As a result, this chemical bond monobloc as described by Freedman (2001) provides a superior and stronger post-and-core complex or restorative continuum. Furthermore, the removal of the smear layer and the adhesion of resin composite to the dentine has been shown to decrease leakage (Freedman and Goldstep, 1997; Tam and Yim, 1997). Intraradicular resin composite rehabilitation of the compromised, root-filled tooth may therefore reduce or eliminate leakage at the coronal end of the root and increase the longevity of the tooth.

An earlier study showed a resin reinforced compromised tooth with a post to have greater fracture resistance when compared to one with a morphologic cast post (Saupe, *et al*, 1996). However, in the latter study, both groups had cast gold posts and cores. Therefore, all the cores were made with the same restorative material and simple comparisons could be done. In this *in vitro* study, both cast and composite cores were used. This illustrates the difficulty one encounters to compare results with similar investigations because of numerous variables. Other variables may include: cores with or without artificial crowns, the rigidity of the material for embedding the tooth, distance from the cemento-enamel junction that the load is applied and/ or the presence of a ferrule.

Significantly higher failure loads were needed to fracture the morphologic post groups. This is mainly due to the higher strength of the nickel-chromium alloy.

However, all the teeth restored with a cast post failed with large oblique root fractures (at significantly high fracture loads, P = 0). Morphologic cast posts and cores may be an alternative restorative option for compromised roots, but their placement is more time consuming (requiring two visits), they have a weaker bond to tooth structure (if traditional cements are used), they provide poor aesthetics for all-ceramic restorations and their eventual catastrophic failure may result in unsalvageable roots (Morgano and Milot, 1993).

There were no significant differences ($p > 0$) in fracture loads between the 3 reinforced tooth groups. These results may have been different if artificial crowns were cemented over the composite cores. Despite a lower resistance, prefabricated posts with composite cores may be a feasible option because most fractures occurred within the composite core, thereby protecting the tooth structure. These reinforced roots can accommodate passive, parallel-sided well-fitting posts and ensure enhanced retention of post crowns in otherwise unretentive, flared root canals. Intra-radicular rehabilitation may increase the potential for salvaging severely compromised teeth and allow their continued serviceability as retentive, functional aesthetic post crowns.

Patterns of failure for all but the cast post-and-core group involved the core portions or core-root interfaces. This corresponds to findings in other studies (Sirimai *et al*, 1999). When an occlusal load is applied, a composite core fracture would be more desirable than a root fracture. All resin–reinforced teeth (with prefabricated posts and composite cores) showed fractures of the composite cores and/ or root fracture. The cervical and oblique root fractures in the cast post-and-core group occurred with significantly higher force than necessary to fracture the composite resin in the resin reinforced groups.

The fact that not a single post fractured may be due to the fact that artificial crowns over the cores were not used. The composite core is weaker than a metal core and this would absorb most of the load and fracture first. In addition, both the glass fiber and carbon fiber posts are reported to have a modulus of elasticity that closely approximates that of dentine. This would allow some bending and recovery when an occlusal force is applied.

CHAPTER SIX: LIMITATIONS OF THIS STUDY

The results obtained in this *in vitro* study do not accurately reflect the situation *in vivo*.

1. None of the teeth were restored with an artificial crown or ferrule. As described by Assif and co-workers (1993), the complete crown with a 2mm ferrule on sound tooth structure changed the distribution of forces to the root and the post-core complex. If complete crowns with ferrules were included, the results of this study may have been different.
2. Fracture resistance was determined by applying a heavy load to a single point; by contrast, in vivo failure typically occurs in response to light or moderate loads applied over a long period.
3. The absence of thermocycling in combination with fatigue loading.

CHAPTER SEVEN: CONLUSIONS

This *in vitro* study evaluated the resistance to failure and the failure patterns of post-core systems that were reinforced with composite resin. The following conclusions can be drawn:

1. Significantly higher fracture thresholds were obtained in the cast post-and-core group.
2. There were no significant differences in fracture loads amongst the three reinforced groups.
3. The reinforced group (with composite cores) showed failure of the post-core interface before the fracture of the tooth occurred. This failure occurred in response to acceptable high loads.
4. The Luminex® light transmitting posts can help strengthen weakened, endodontically treated teeth by the combined bonding action of dentine bonding agents and composite resin restorative material.

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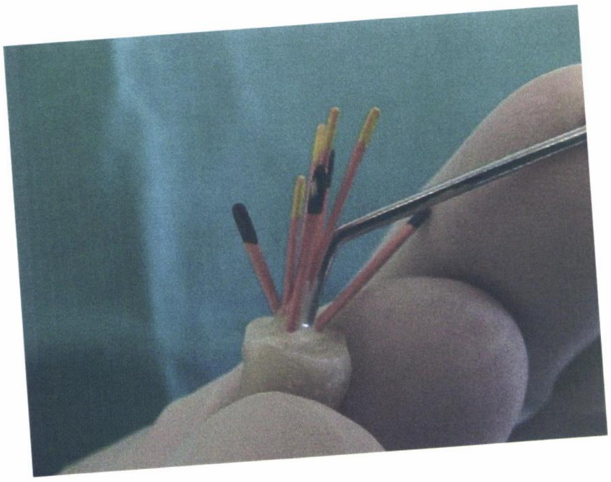
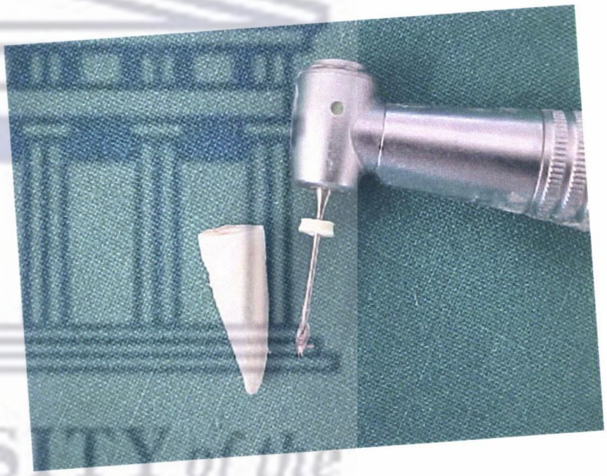
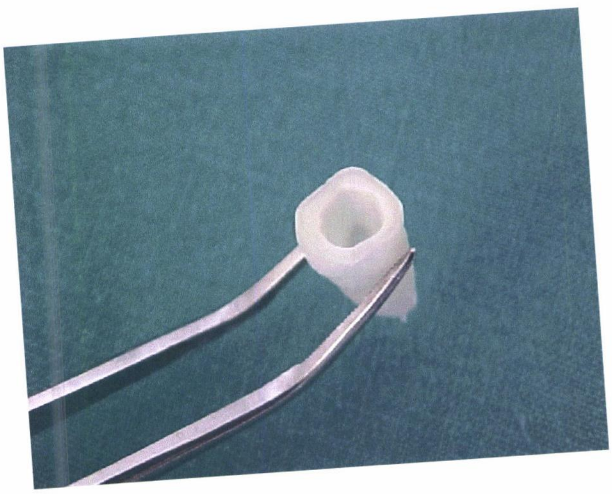
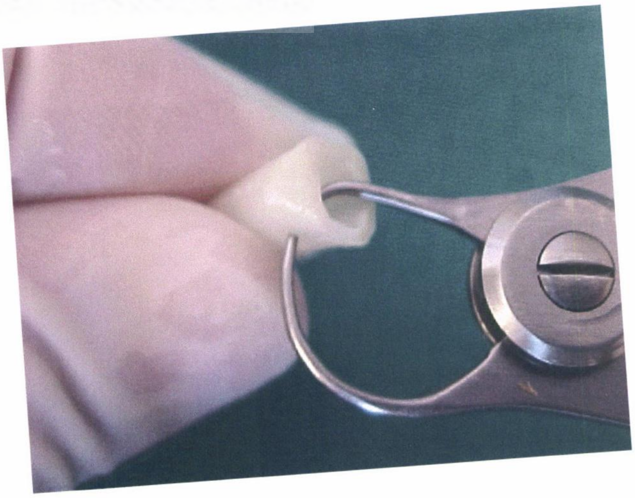
Appendix 1: Tooth preparation









Appendix 4: Results for all Tooth Specimens

ToothNo:	Rootlength	BL	MD	Circum	Post	# Load	Dentine #
1	16.5	7.0	6.0	22.0	C	2,111.00	Y
2	13.0	6.0	5.2	20.0	FW	538.99	Y
3	16.0	6.4	6.1	20.0	TI	768.33	Y
4	15.0	7.2	6.4	22.0	AL	1,010.68	Y
5	18.0	6.4	4.6	18.0	AL	666.36	Y
6	17.0	7.6	6.3	21.0	C	2,111.00	Y
7	17.0	6.5	6.1	21.0	FW	502.91	N
8	18.0	7.3	5.8	20.0	C	1,391.75	Y
9	22.0	6.6	5.3	20.0	C	2,111.00	Y
10	16.0	6.6	4.9	19.0	AL	813.74	Y
11	16.5	6.9	5.6	19.0	TI	697.84	Y
12	15.5	6.4	6.3	21.0	C	2,111.00	Y
13	14.0	6.9	5.6	20.0	TI	1,195.85	N
14	18.0	6.6	5.0	20.0	AL	752.47	Y
15	17.0	6.1	5.8	20.0	C	672.55	Y
16	13.0	6.0	6.1	20.0	AL	501.43	Y
17	15.0	7.3	6.4	22.0	C	2,111.00	Y
18	15.0	5.5	4.2	16.0	AL	691.68	Y
19	17.0	7.5	6.1	22.0	TI	911.86	Y
20	16.5	6.2	6.1	20.0	AL	645.61	Y
21	18.5	7.1	5.1	20.0	C	1,496.06	Y
22	16.0	6.3	4.2	21.0	FW	858.06	Y
23	16.0	6.9	5.1	24.0	FW	618.38	Y
24	17.0	7.2	6.7	21.0	TI	659.10	Y
25	14.0	6.5	5.9	21.0	C	1,859.22	Y
26	16.0	6.4	5.5	21.0	FW	1,200.59	Y
27	15.0	6.9	5.7	20.0	AL	588.09	Y
28	17.0	7.0	4.7	20.0	TI	654.24	Y
29	16.0	7.1	5.1	21.0	AL	553.61	N
30	14.5	6.2	5.2	23.0	FW	753.65	Y
31	15.0	6.5	6.3	21.0	AL	455.32	Y
32	19.0	6.5	6.8	22.0	AL	948.56	Y
33	15.0	6.7	6.2	20.0	AL	643.22	Y
34	16.0	6.0	5.4	20.0	FW	414.30	Y
35	16.0	5.7	4.7	18.0	TI	398.61	Y
36	17.0	6.6	5.7	21.0	TI	410.59	Y
37	15.0	6.8	6.1	21.0	C	2,111.00	Y

ToothNo:	Rootlength	BL	MD	Circum	Post	# Load	Dentine #
38	14.0	5.7	4.0	16.0	C	988.05	Y
39	15.0	6.2	5.4	21.0	FW	587.17	Y
40	11.0	6.4	4.9	20.0	TI	786.43	Y
41	16.0	5.9	4.2	18.0	AL	558.45	Y
42	16.0	6.3	5.3	19.0	FW	587.64	Y
43	17.0	6.2	5.4	20.0	AL	637.24	Y
44	14.0	5.7	4.1	18.0	AL	495.87	Y
45	16.0	6.0	3.8	16.0	FW	533.51	Y
46	15.0	5.9	4.9	19.0	TI	351.62	N
47	17.5	6.5	4.7	19.0	FW	969.44	Y
48	12.0	6.7	5.9	20.0	C	1,275.79	Y
49	16.0	6.9	4.7	20.0	C	2,111.00	Y
50	15.0	6.2	5.9	20.0	AL	778.01	Y
51	17.0	6.1	5.1	19.0	C	799.80	Y
52	21.0	7.0	6.6	22.0	FW	778.01	Y
53	15.0	6.2	5.3	20.0	TI	781.31	Y
54	17.0	6.7	6.3	20.0	C	1,078.52	Y
55	15.0	5.7	5.5	19.0	AL	659.57	Y
56	16.5	6.9	5.3	19.0	AL	821.49	Y
57	17.0	5.9	4.9	19.0	TI	481.52	Y
58	13.0	6.1	5.0	19.0	C	2,111.00	Y
59	15.0	7.2	6.3	21.0	TI	650.69	N
60	18.0	6.8	5.1	19.0	TI	1,032.28	Y
61	15.0	6.0	4.9	19.0	FW	668.71	Y
62	17.0	6.3	4.4	18.0	FW	411.70	Y
63	15.0	6.4	4.6	17.0	FW	826.60	Y
64	16.5	7.0	4.4	19.0	TI	620.46	Y
65	16.0	6.0	4.3	18.0	AL	617.05	Y
66	17.5	7.3	4.4	20.0	TI	623.65	Y
67	21.0	7.1	4.6	21.0	AL	774.69	Y
68	17.0	7.0	5.7	21.0	C	1,326.14	Y
69	17.0	7.6	5.9	21.0	C	1,282.70	Y
70	17.0	5.8	4.7	19.0	TI	575.95	N
71	22.0	5.0	5.3	17.0	FW	651.11	Y
72	15.0	6.4	4.8	19.0	TI	478.09	N
73	13.0	5.9	5.0	19.0	TI	346.41	N
74	13.0	6.2	5.1	19.0	C	2,111.00	Y
75	12.0	6.0	4.7	18.0	FW	556.66	Y
76	15.0	6.5	5.0	20.0	AL	885.24	N
77	14.0	6.3	5.7	20.0	C	2,111.00	Y
78	16.0	6.7	5.2	19.0	FW	705.19	Y

ToothNo:	Rootlength	BL	MD	Circum	Post	# Load	Dentine #
79	19.0	6.1	6.4	20.0	FW	572.80	Y
80	15.0	7.5	5.8	21.0	FW	746.22	Y
81	12.0	6.2	5.4	20.0	TI	616.56	Y
82	16.0	6.5	5.4	20.0	FW	674.12	Y
83	18.0	6.6	6.1	20.0	AL	223.82	Y
84	14.0	6.1	5.9	20.0	TI	711.20	Y
85	18.0	6.4	5.9	21.0	AL	959.03	Y
86	16.0	6.6	5.1	19.0	AL	1,066.46	Y
87	17.0	5.9	4.7	22.0	TI	870.04	Y
88	14.0	6.4	6.3	20.0	FW	169.60	Y
89	15.5	6.8	6.3	20.0	C	1,042.87	Y
90	15.0	6.2	5.8	20.0	FW	738.11	Y
91	17.0	5.6	5.0	18.0	FW	538.87	Y
92	15.0	6.8	5.7	20.0	C	2,000.26	Y
93	15.0	6.9	5.7	22.0	TI	860.22	Y
94	16.0	5.2	4.3	19.0	AL	511.27	Y
95	14.0	6.0	4.5	17.0	TI	835.21	Y
96	15.0	6.6	5.7	21.0	AL	464.61	Y
97	17.0	6.6	4.6	18.0	C	1,735.80	Y
98	16.0	6.6	5.0	20.0	FW	722.79	Y
99	16.0	6.9	5.1	20.0	C	2,111.00	Y
100	18.0	6.6	6.4	21.0	C	1,664.84	Y

MD= Mesiodistal; BL = Bucco-lingual; Circum = Circumference; # = Fracture; C = Cast Post; FW = Carbon Fiber (FiberWhite®) Post; Ti = Titanium Post; AL = Glass Fiber (Anchor Luscent®) Post.

Appendix 5: Statistics Records : Fracture Loads

# L_al	# L_c	# L-fw	# L_ti
1010.68	2111.00	538.99	768.33
666.36	2111.00	502.91	697.84
813.74	1391.75	858.06	1195.85
501.43	2111.00	618.38	752.47
691.68	2111.00	1200.59	911.86
645.61	672.55	753.65	659.10
588.09	2111.00	414.30	654.24
553.61	1496.06	587.17	398.61
455.32	1859.22	587.64	410.59
948.56	2111.00	533.51	786.43
643.22	988.05	969.44	351.62
558.45	1275.79	778.01	781.31
637.24	2111.00	668.71	481.52
495.87	799.80	411.70	650.69
778.01	1078.52	826.60	1032.28
659.57	2111.00	651.11	620.46
821.49	1326.14	556.66	623.65
617.05	1282.70	705.19	575.95
774.69	2111.00	572.80	478.09
885.24	2111.00	746.22	346.41
223.82	1042.87	674.12	616.56
959.03	2000.26	169.60	711.20
1066.46	1735.80	738.11	870.04
511.27	2111.00	538.87	860.22
464.61	1,664.84	722.79	835.21

 # = Fracture; C = Cast Post; FW = Carbon Fiber (FiberWhite®) Post; Ti = Titanium Post; AL = Glass Fiber (Anchor Luscent®) Post.

# L_al		# L_c		# L-fw		# L_ti	
n	678.844	Mean	1673.414	Mean	653.0052	Mean	682.8212
lian	645.61	Median	1859.22	Median	651.11	Median	659.1
ndard Deviation	199.4522	Standard Deviation	490.74363	Standard Deviation	199.9358	Standard Deviation	208.86145
nple Variance	39781.19	Sample Variance	240829.31	Sample Variance	39974.31	Sample Variance	43623.106
ge	842.64	Range	1438.45	Range	1030.99	Range	849.44
mum	223.82	Minimum	672.55	Minimum	169.6	Minimum	346.41
imum	1066.46	Maximum	2111	Maximum	1200.59	Maximum	1195.85
nt	25	Count	25	Count	25	Count	25
gest(2)	1010.68	Largest(2)	2111	Largest(2)	969.44	Largest(2)	1032.28
allest(2)	455.32	Smallest(2)	799.8	Smallest(2)	411.7	Smallest(2)	351.62