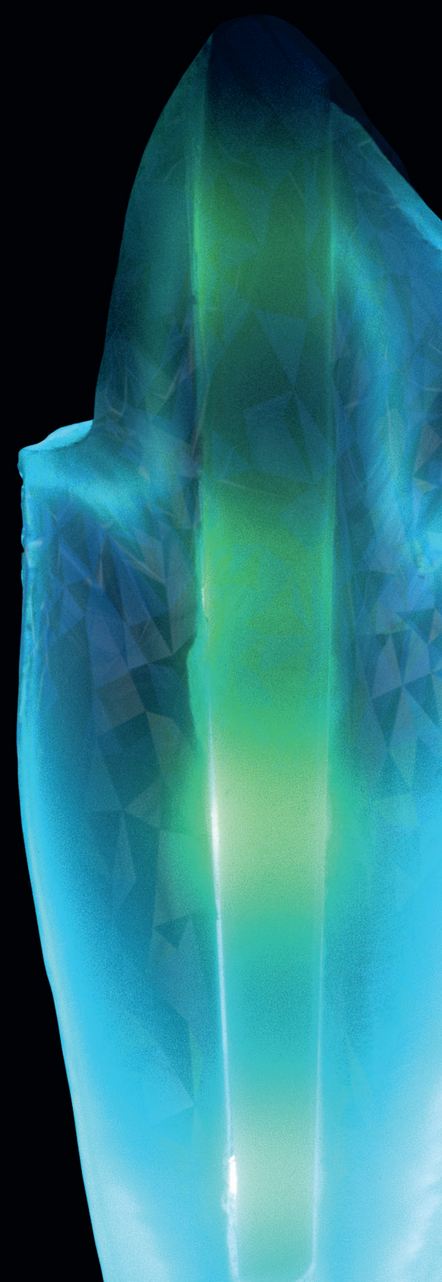
Douglas A. Terry, DDS

RESTORING THE INTRARADICULAR SPACE: ESTHETIC POST SYSTEMS



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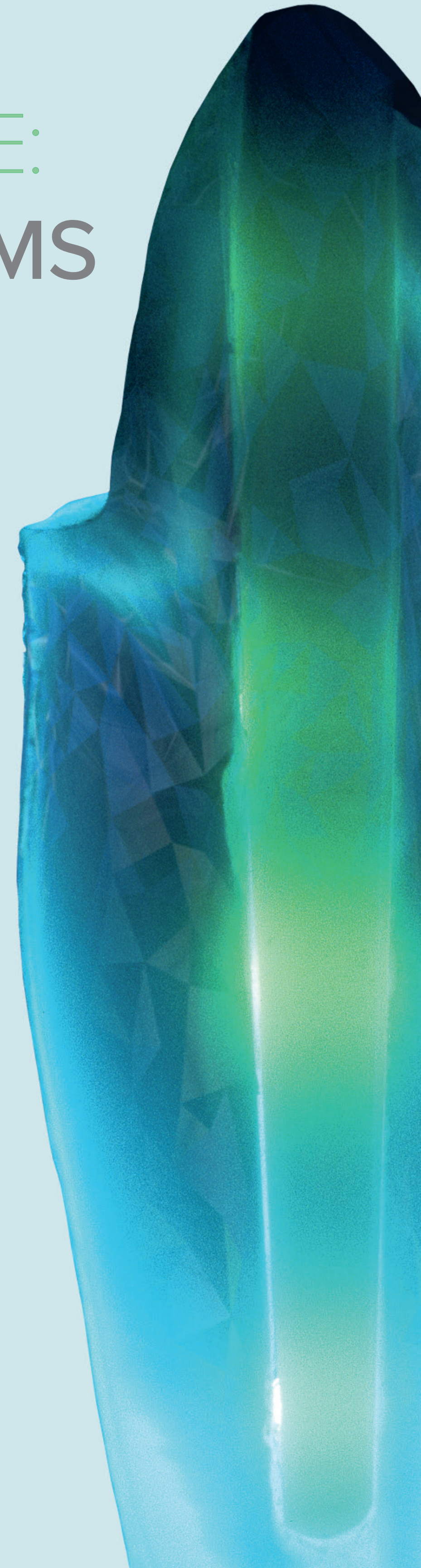

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FOREWORD

There is a question I always ask myself, my students, and my colleagues: "What is our single most important responsibility as an oral health care provider?" While there may be various interpretations of our core duties, I always come to the same simple but resounding answer: "To help our patients keep their teeth as long as possible!"

To pursue this goal and preserve teeth, we have to emerge from the era of destructive dentistry, which dates back to times before resin bonding and adhesive protocols were available. Healthy tooth structure had to be sacrificed during preparation to accommodate restorative and prosthetic materials that relied solely on retention. The popularity of implant dentistry sometimes added to this destructive mindset when teeth were extracted and implants placed too early or inadequately, thereby accelerating the cascade of early tooth loss instead of following the core principle of preservation. The rush to the seemingly easiest but most destructive treatment options may lead to early tooth loss, bone and tissue resorption, peri-implantitis, and altered eruption of teeth next to implants that were placed in younger patients.

Several new studies agree that the recommended age when dental implants can be placed safely is going up and up, making a strong case to preserve even severely damaged and endodontically treated teeth as long as possible. Don't get me wrong: I have nothing against implants, and in many cases, they are the last and absolutely best resort to provide our patients with chewing function and esthetics. However, they are the last resort when everything else fails. And the argument I often hear that "implants last longer than teeth" is not only completely wrong but not even a logical argument for erring on the side of placing implants earlier instead of exploiting all resources to try and save a natural tooth. While some of that rationale may, sadly, be driven by convenience and economic aspects, I believe that the most important factors in the treatment-planning decision-making process are proper knowledge and information.

The most difficult treatment-planning decisions are related to the severely damaged endodontically treated tooth. The amount of misinformation on this topic is simply astonishing. What is the state of the scientific evidence on endodontically treated teeth and how to restore them? When should a post be placed? And in light of this era of minimally invasive and adhesive dentistry, what are the best materials and most current protocols for post and core placement, based on the science?

Douglas, author of many groundbreaking and bestselling books, has compiled a team of the most respected researchers and clinicians to answer these questions and provide clear guidance on a topic that seems to have been widely overlooked. *Restoring the Intraradicular Space:*

Esthetic Post Systems provides a detailed and scientific description of the evolution of post and core systems while offering a comprehensive view into all associated aspects, from general design criteria and the components of the post and core systems to post materials, adhesive bonding and luting agents, material selection, core buildup, and finally, the extracoronal restoration. The dilemma of preserving or replacing the compromised natural tooth is discussed in great detail with ample scientific support. Over 1,000 cited research studies are distilled into clear and meaningful guidelines for the clinician to select an appropriate system for the restorative management of endodontically treated teeth for each clinical situation. In well-known Douglas Terry manner, clinical protocols are illustrated meticulously and with stunning quality with over 800 photographs and figures.

To fulfill our responsibility to help patients keep their teeth as long as possible, understanding and selecting proper protocols, materials, and procedures to restore endodontically treated teeth is indispensable. While a comprehensive text on this topic was long overdue, *Restoring the Intraradicular Space: Esthetic Post Systems* is not only an exceptional resource for the practicing dentist but a true masterpiece in its scientific rigor and clinical excellence. The captivating writing and superb clinical documentation make this an essential piece of literature for oral health care providers at any stage of their career. Congratulations Douglas and team—I am sure that your work will inspire countless colleagues and prevent many patients from losing their teeth too early. Thank you for that!

Markus B. Blatz, DMD, PhD, Dr med dent habil
Chairman, Department of Preventive and Restorative Sciences
Assistant Dean for Digital Technologies and Professional Development
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PREFACE

Recently I read a comment by a dentist saying "every root has a chance." This statement resonated with my philosophy because it is not only the tooth but also the alveolar and soft tissue architecture and the patient that deserve a chance. Over the last decade I have witnessed patients presenting with fractured teeth that were referred for removal and implant placement. Upon discussion with them, it became clear that not everyone was given proper informed consent; some were offered only the one treatment option. So I would explain the how's and why's of every option, and then the patient could make the proper choice for their oral health. Individuals make better decisions when they are given all the potential options and the consequences of each.

A recent conversation with a young periodontist on my team further underscored this problem. He told me that his referring dentists do not try and save a given tooth with a post and core. In discussing this with my friend and colleague Dr Konrad Meyenberg in Switzerland, we considered that perhaps the reason was the lack of confidence clinicians have in the endodontic therapy and in their knowledge of proper adhesive protocol. This extraction-oriented, reconstructive mentality may be based on the clinicians' misconception that endodontically treated teeth are considered inferior to implants in regard to long-term stability and retention. However, it has been demonstrated that endodontic and implant therapies have equivalent results when the treatments are appropriately chosen and performed at a high level of expertise on well-maintained patients.

Throughout these chapters, I would like the reader to direct their attention to modern applications in the fields of endodontics, restorative dentistry, periodontics, and orthodontics. In the past two decades, dentistry has seen a paradigm shift in philosophy that has been guided by a greater understanding of science. Advancements in endodontic technology with the use of modern instruments and new equipment, biocompatible filling materials, and microsurgical techniques have allowed the clinician to visualize, identify, and treat complexities they could not have fathomed a decade before. Correspondingly, advancements in restorative material formulations, adhesive technology, and a better understanding of the methods to achieve a biologically stable, dentogingival interface through periodontal and orthodontic concepts have expanded the treatment possibilities for the patient, clinician, and technician. Furthermore, clinicians should not make treatment decisions based on their skill level alone but should refer or adopt an interdisciplinary approach when required for the management of more complex clinical scenarios.

These advances in all disciplines in the 21st century have increased the myriad opportunities available to discriminating patients and provided solutions to many of the endodontic, restorative, and esthetic challenges faced by the restorative team. This changing technology has allowed the clinician to treat many clinical challenges through simpler, more conservative, and more economical methods. This evolution in philosophy and science has resulted in a change in the trend for dental treatment. Thus, an awareness in the evolution of different disciplines in dentistry combined with the common occurrence of misinformed patients coming for another opinion stimulated my team and me to develop this book. This philosophy of choosing the least invasive procedure and moving to a more invasive one if required over time is an ethical one. I hope the concepts in this book direct the clinician and technician to consider possibilities they had not imagined.

The text provides a detailed and scientific description of the evolution of the post and core system and the significance of the adhesive design concept when restoring the intraradicular post space. A detailed presentation is provided of the various applications and restorative techniques that I use on a daily basis with my patients for restoring the post space. The scientific data and microscopic illustrations are intertwined to provide clarity and evidence for these procedures. In addition, chapter 2 provides a detailed description of the light-curing unit (by Dr Richard Price) and the significance of understanding its mechanism for proper selection and use, which play an integral role in the adhesive design concept for achieving an optimal bonded interface. The third chapter demonstrates the information presented in the early chapters through illustrated case presentations while providing clinical applications for retaining the compromised tooth. The last chapter demonstrates clinical scenarios for the replacement and restoration of the nonrestorable endodontically treated tooth or the “end stage” tooth, while providing various treatment considerations and the critical factors that may play a role in the selection, outcome, and predictability of each of these treatment modalities.

Acknowledgments

As always, the inspiration for writing this book and sharing photographs of these procedures can be attributed to my dear patients, colleagues, and students around the world who have directed me on this journey. Compilation of this information would not have been possible without the dedication, persistence, and relentless hard work and long hours of my dear friend and personal assistant, Melissa Nix. My mother’s great ability to persuade patients to return for follow-up photographs along with her support and delicious dinners and desserts for the team have certainly been crucial for completing this project. Furthermore, this book would not have seen the light of day without the dedication, attention to detail, and organization and imagination of the Quintessence team. I would also like to express my gratitude to my team members who are my true friends—Dr John Powers, Dr John Burgess, Dr Ruhani Cheema, Dr Markus Blatz, Dr Susana Paoloski, Dr Gamid Nasuev, Alex Schueger, Olivier Tric, and Dr Richard Price. Also, I would like to thank my wonderful patients, without whom this project would not have been possible. Finally, I give special thanks to my Creator who instills passion in my life for everything I do and who makes me realize that teeth are simple in His hands but so complex in mine.

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Truth is expressed in different languages around the world.

The Pursuit of the Truth

"What is truth" is a question that has been asked by philosophers, scientists, and religious prophets for centuries.

Truth can be defined as that which conforms to facts, reality, and actuality. But this definition has a broad latitude of interpretation and application. If we say truth can be relative or absolute, this may differentiate and lead to a better understanding and application. Relative truth conforms to logic and reality and can be interpreted differently by every person based upon their culture, religion, and life experiences. However, absolute truth requires each of us to search and discover something greater than ourselves.

God is the true essence of being and the absolute truth. The Bible describes the ultimate expression of truth in John 14:6: "I am the way, the truth, and the life."

Photography by Irfan Ahmad, BDS

1

ESTHETIC POST SYSTEMS

HISTORICAL PERSPECTIVE

For over 250 years, clinicians have written about the placement of posts in the roots of teeth to retain restorations.[1,2] As early as 1728, Pierre Fauchard described the use of "tenons," or metal posts screwed into the roots of teeth to retain bridges.[1,3–6] In the mid 1800s, wood replaced metal as the post material, and the "pivot crown" became popular among dentists; this was a wooden post fitted to an artificial crown and the canal of the root.[1,2,7] Often these wooden posts would absorb fluids and expand, frequently causing root fractures.[4,7] In the late 19th century, the "Richmond crown," a single-piece post-retained crown with a porcelain facing, was engineered to function as a bridge retainer.[2,7] During the 1930s, the custom-cast post and core was developed to replace the one-piece post crowns. This procedure required casting a post and core as a separate component from the crown.[7] This two-step technique improved marginal adaptation, allowed variation in the path of insertion of the crown,[1] and provided a better alignment of the core when the tooth being restored was flared or overlapped the adjacent tooth. In the 1990s, tooth-colored fiber posts debuted as an alternative to these conventional metal post systems.[8–17]

From the past to the present, the rationale for the utilization of a post system has metamorphosed. The concepts of the past were designed with the belief that endodontically treated teeth (ETT) were brittle from a loss of moisture[18,19] and required a post to strengthen the weakened tooth.[20–26] Although there is a reduction in moisture content after endodontic treatment, current concepts refute this postulate.[18,19,27–36] Current concepts supported by evidence-based research indicate that the primary objective of any post and core system is to replace missing coronal tooth structure, to retain the core,[37–44] and to provide sufficient retention[41,43,45–54] and resistance form to the final restoration to restore original form and function.[37–39,55–69] Today, clinicians can choose from a variety of user-friendly post and core systems[29,70–81] for different endodontic, restorative, and esthetic requirements. These systems and methods are well documented in the literature.[23–25,29,40,42,80–99] However, no single post system meets the demands for favorable biomechanical compatibility[65,80,100–102] or provides the perfect restorative solution for every clinical circumstance, and each situation requires an individual evaluation.[82]

Furthermore, the reconstruction of ETT can present restorative and esthetic challenges for the technician and the clinician.[9,80,103–105] The failure of these post-retained systems has been documented in numerous clinical studies.[22,39,45,51,66–68,101,106–150] Many of these studies indicate that the failure rate of restorations on pulpless teeth with posts and cores is higher than that for restorations of vital teeth[106,151–163] because of their structural differences and the significant loss of tissue.[36] Several main causes of failure of post-retained restorations have been identified, including recurrent caries,[164,165] endodontic failure,[165] periodontal disease,[165] post dislodgment,[165] cement failure,[166] post-core separation,[165] crown-core separation,[165] loss of post retention,[40,164] core fracture,[152] loss of crown retention,[40,164] post distortion,[164] post fracture,[40,152,164,166] tooth fracture,[152,166] root perforation,[40] and root fracture.[40,152,164,167,168] Also, corrosion of metal posts has been proposed as a cause of root fracture.[152] A post and core system fabricated with dissimilar metals can cause galvanic corrosion that occurs between the two dissimilar materials.[19,169] This gradual destructive process involves the electrical interaction of at least two different metals or nonmetallic conductors in an environment (ie, microleakage) that accelerates the corrosion of at least one of them, while the least noble metal corrodes the most (for more information, see the section entitled "Lack of corrosiveness" later in this chapter).

The traditional custom-cast dowel core provides a better geometric adaptation to excessively flared or elliptical canals and almost always requires minimal removal of tooth structure.[1] Custom-cast posts and cores adapt well to extremely tapered canals or those with a noncircular cross section and/or irregular shape and roots with minimal remaining coronal tooth structure.[82,89] Patterns for custom-cast posts can be formed either directly in the mouth or indirectly in the laboratory. Regardless, this method requires two appointment visits and a laboratory fee. Also, because it is cast in an alloy with a modulus of elasticity that can be as high as 10 times greater than that of natural dentin,[55] this possible incompatibility and rigidity can create stress concentrations in the less rigid root, resulting in post separation or failure.[170–172] Additionally, the transmission of occlusal forces through the metal core can focus stresses at specific regions of the root, causing root fracture[55] (Fig 1-1). Furthermore, upon esthetic consideration, the cast-metal post can result in discoloration and shadowing of the gingiva and the cervical aspect of the tooth[173] (Fig 1-2).

An alternative and currently more popular method is the prefabricated post and core system. Prefabricated post and core systems are classified according to their geometry (ie, shape and surface configuration) and method of retention. The methods of retention are designated as active or passive. Active posts engage the dentinal walls of the post space preparation during cementation, whereas passive posts do not engage the dentin but rely on cement for retention.[1,174] The basic post shapes and surface configurations are tapered serrated, tapered smooth-sided, tapered threaded, parallel serrated, parallel smooth-sided, and parallel threaded. While active or threaded posts are more retentive[175–178] than passive posts, active posts create high stress concentrations in root dentin at each thread during placement.[177,179–184] These stresses have the potential to create cracks[185,186] that can increase the susceptibility of root fracture[127,184] when occlusal forces are applied.[10] Thus, a significant cause of failure with an active post system is root fracture.[52,184,187,188] More recent modern designs provide a collar that limits insertion, flexible tips (FlexiPost), and stress-reducing thread design. Metal screws have a survival rate of 78%[127,184] after 1 year and 50% after 5 years.[184]

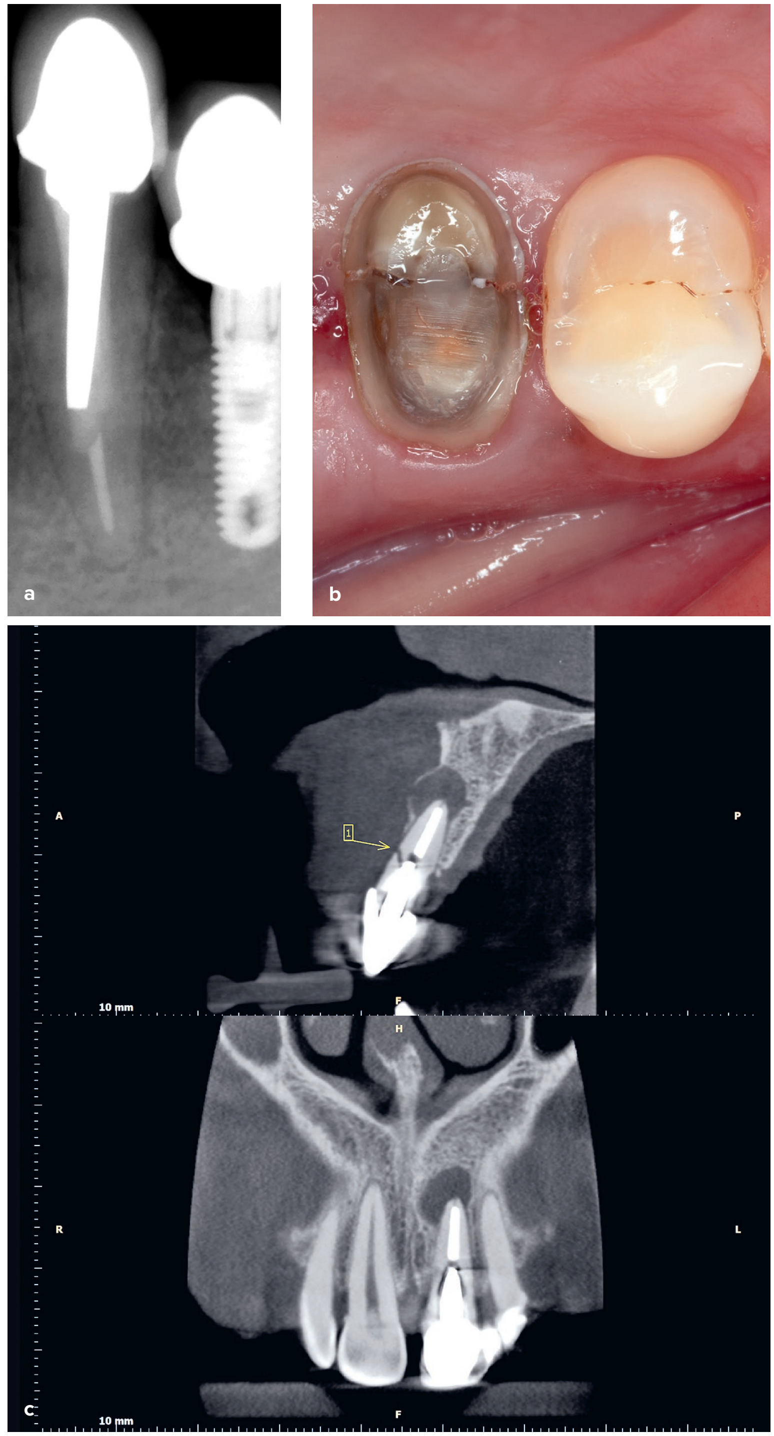
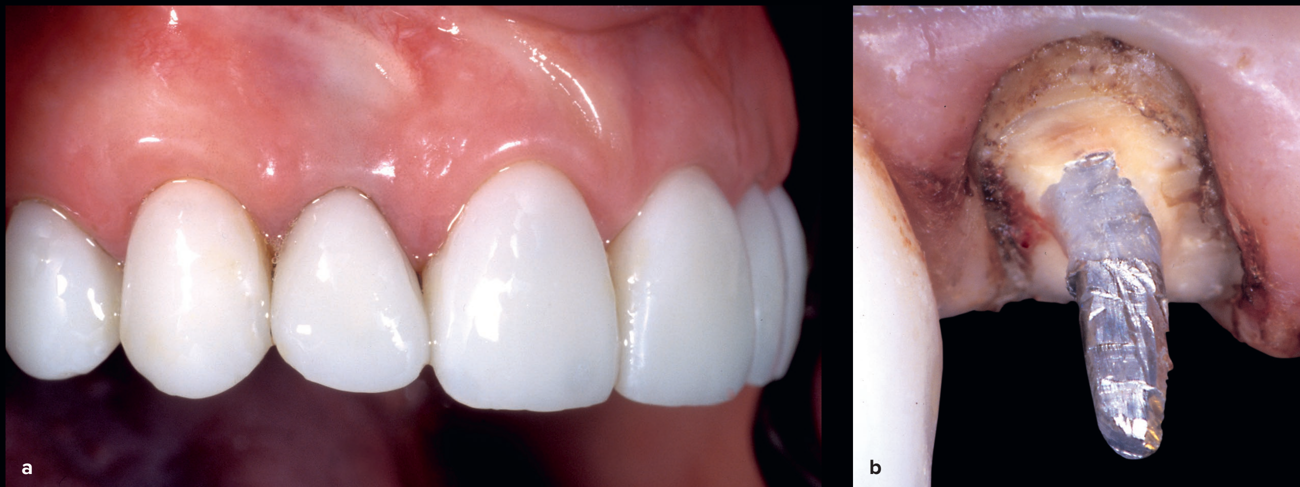


Fig 1-1 *(a)* Occlusal forces are transmitted through the metal post in the mandibular right canine, and stress concentrations are focused in the mesial aspect of the apical one-third of the root, resulting in a horizontal fracture. *(b)* A vertical fracture occurs in the maxillary right second premolar with a metal post present. *(c)* A CBCT shows a horizontal fracture in the maxillary left central incisor. (Radiograph courtesy of Ritu Sharma, BDS, MDS.)



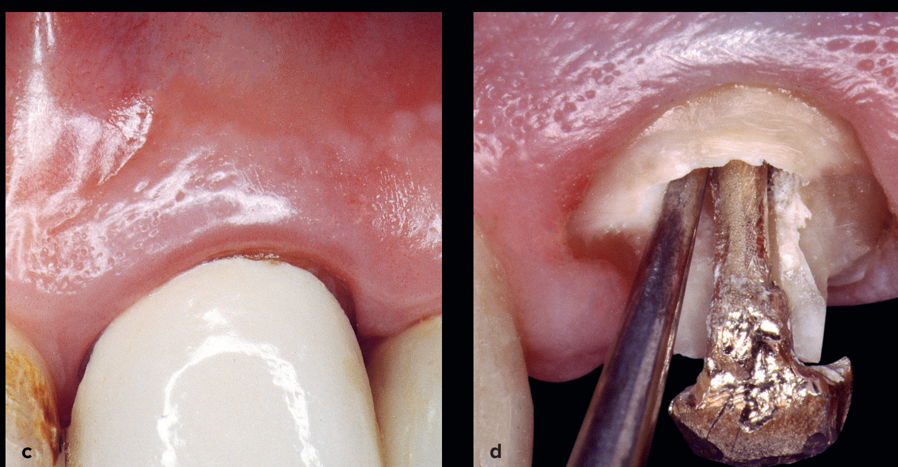


Fig 1-2 *(a and b)* A maxillary right lateral incisor is restored with a cast-metal post. This can result in discoloration and shadowing of the gingiva and the cervical aspect of the tooth. *(c to e)* The incidental light is completely blocked by the metal post and the underlying metal framework of the crown, which causes the characteristic shadow at the submarginal zone.

Fig 1-3 Posts and cores fabricated from materials with a high modulus of elasticity and a combination of noble and non-noble alloys in the oral environment may result in electrochemical reactions such as corrosion of metals, which can cause root fracture.

Parallel-sided serrated posts are the most retentive of the passive prefabricated posts, and the tapered smooth-sided posts are the least retentive of all designs.[7]

Traditional prefabricated metal posts are made of platinum-gold-palladium, brass, nickel-chromium (stainless steel), pure titanium, titanium alloys, and chromium alloys.[7,37–39,164] Although stainless steel is stronger, the potential for adverse tissue responses to the nickel has resulted in the use of a biocompatible titanium alloy.[189,190] Also, contributing factors to root fracture such as excessive stiffness (modulus of elasticity)[191–193] and post corrosion[7,121] (Fig 1-3) from many of these metal posts have generated concerns about their use. In addition, prefabricated metal posts can negatively affect the esthetic result.

Nonmetallic prefabricated posts have been developed as alternatives,[194] including ceramic (white zirconia) posts, carbon-fiber posts, and fiber-reinforced resin posts. Zirconia posts have a high flexural strength and are biocompatible as well as corrosion resistant.[195] This material, however, is difficult to section intraorally with a diamond bur and difficult to remove from the canal for retreatment.[164] Carbon-fiber posts are made from unidirectional carbon fibers held together with an epoxy resin and ceramic. They exhibit strength and relatively high flexibility and can be retrieved from the canal preparation with ease for retreatment. However, their black color has a negative effect on the final esthetic result of all-ceramic crowns.[189] New advances with next-generation tooth-colored posts, which are identical in design to conventional carbon-fiber posts, reduce this esthetic challenge. There are several methods for the fabrication of the direct fiber-reinforced resin system that include a bondable polyethylene woven reinforcement fiber (Ribbond-THM, Ribbond; Construct, Kerr/Sybron), a prefabricated fiber-reinforced composite post system, a direct anatomical formed fiber-reinforced composite post system,[105,195,196] a direct/indirect anatomical formed fiber-reinforced composite post system, and an indirect anatomical formed fiber-reinforced composite post system (see the section entitled “Direct Fiber-Reinforced Post and Core System” later in this chapter).

CONSIDERATIONS FOR THE SELECTION OF RESTORATIVE MATERIALS

As the clinician continues the search for optimal functional and esthetic success with a post-retained crown system, the current selection of restorative materials and techniques may prove overwhelming. While no single system provides the ideal restorative solution for every clinical circumstance, understanding both general design criteria and the components for the various post and core systems available allows the clinician to appropriately select the method and materials compatible with the existing tooth structure and desired result. A *system* is defined as any set of components working together for the overall objective of the whole.[1] Selecting the proper post and core system for a specific clinical situation requires an evaluation of the various components and interfaces of the system.[197,198] The components of the direct fiber-reinforced composite resin post system are the surface of the root dentin, the intraradicular post, the core buildup, the luting cement, and the final restoration[199] (Fig 1-4). The system can be analyzed in four regions: *(1)* at the intraradicular surface (dentin surface), *(2)* at the post-tooth interface, *(3)* within the core, and *(4)* intracoronally. For the successful rehabilitation of the ETT, it is imperative to understand the disparity and complexity of the interrelationship of these interfaces with various restorative materials.[55] The failures of each system provide us with design principles that can be utilized with any post-retained crown system. These specific design principles bring us to higher levels of understanding potential problem areas in any restorative situation. Therefore, the following design principles should be considered when using any post-retained crown system. An evaluation of the direct fiber-reinforced resin post system with these design principles is provided.

Maximum post retention and core stability

Dislodgment and tooth fracture are causes for failure of post and core restorations. The majority of clinical failures involving fiber-reinforced post systems occur through debonding.[15,29,45,80,100,119,120,124–126,200–215] Core stability and post retention are important in preventing these failures in the restoration of ETT[51,105,164,166,168,177,193,216–218] (Fig 1-5). The ideal post system should replace lost tooth structure while providing adequate retention and resistance for the core and final restoration while transferring occlusal forces during function and parafunction to prevent root fracture. Adhesive post systems allow conservative minimally invasive preparations that preserve sound tooth structure and strengthen the remaining tooth. However, meticulous adhesive protocols are required for reliable bonding and effective adhesion. Improving the quality of the adhesive interface and the long-term adhesion of fiber-reinforced post systems to dentin requires improving resin impregnation into dentin,[212,219–227] enhancing the strength of the polymer formed by the adhesive system,[212,228–252] and increasing the resistance of collagen fibrils to enzymatic degradation.[212,253–273] Because the root canal anatomy can impose limitations to achieving a quality hybrid layer, modified clinical protocols have been suggested. Studies indicate that various methods and materials can improve the stability of the resin-dentin bond.

Numerous studies suggest methods and materials to improve resin impregnation into dentin. One study indicates that diamond bur preparation of the post channel in comparison to a carbide bur allows the etching procedure to remove the smear layer more efficiently with more open dentinal tubules and with fewer smear layer remnants. Thus, the acid-resistant smear layer produced by the manufacturer's carbide bur for post space preparation can be removed with a similar-diameter diamond bur, and the replaced smear layer will be more susceptible to phosphoric acid dissolution.[212,220] Other studies indicate that liquid phosphoric acid applied with an endodontic needle improved the removal of the smear layer better than

Fig 1-4 The five components of the post-retained crown system are the internal root dentin surface, luting cement, intraradicular post, core buildup, and the crown. The system can be analyzed at each of the four interfaces: at the dentin surface, at the post-tooth interface, within the core, and intracoronally.

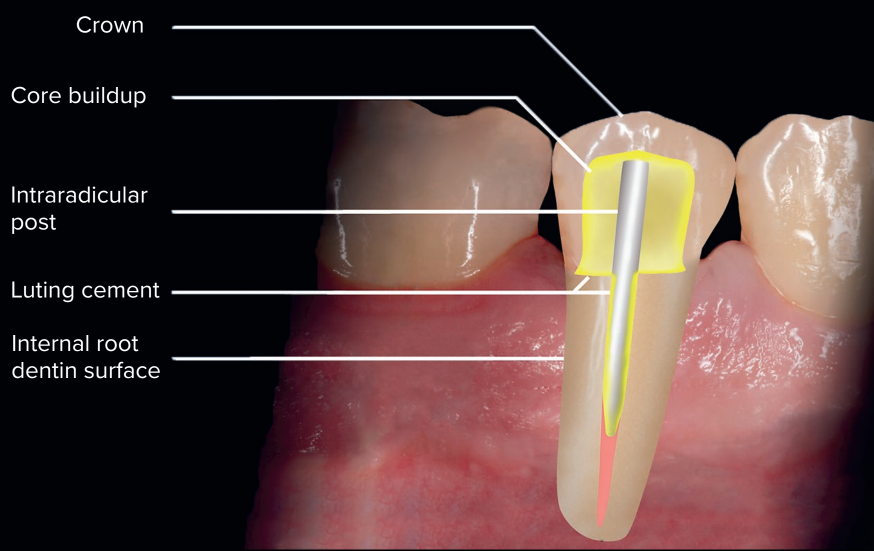


Fig 1-5 *(a to c)* Failure of a post-retained system. The metal-ceramic crown with gold post dislodges form the intraradicular space as a result of microleakage and recurrent caries at the interface.

gel etchants and that higher bond strengths to the dentin were achieved when an etch-and-rinse adhesive system was utilized.[212,226,227] Several studies indicate that vigorous rubbing of the adhesive may improve the permeability of the etchant into the dentin collagen network.[223,224] Other studies indicate that the application of multiple layers of simplified etch-and-rinse adhesives and self-etch adhesives to coronal dentin yield higher immediate bond strengths.[221,222] However, this modified protocol should be applied with caution to prevent post seating because of the increase in thickness of the hybrid layer. It is suggested that paper points or a vacuum capillary tip adapter (Luer Vacuum Adapter, Ultradent) can be utilized to absorb the excess solvent.[212]

Various studies suggest methods and materials to enhance the strength of the polymer formed by the adhesive system. Studies indicate that the use of a hydrophobic coating after the application of a simplified self-etch adhesive and an etch-and-rinse adhesive system provides a thicker and more uniform adhesive layer with lower concentrations of water and solvent and thus a significant reduction in fluid flow rate.[235,240] This procedure transforms a simple-layer adhesive into a multilayer adhesive. This method ensures that the hydrophilic layer is photoactivated prior to the application of the hydrophobic, non-solvated bonding resin. This allows for the simplified adhesive layer to be more concentrated with hydrophobic monomers from the additional coating.[212,232,241] Thus, by reducing the concentration of unreacted monomers between the primed and bonded layers, a more compacted and stable resin-dentin interface can be achieved.[212,235] However, this modified protocol should be applied with caution to prevent a thick adhesive layer that could interfere with post seating.[212] Numerous studies suggest that the application of ethanol to replace water in acid-etched collagen will allow hydrophobic resins to infiltrate the demineralized dentin and create a hydrophobic hybrid layer.[231,239,242,252] Because endogenous matrix metalloproteinases (MMPs) become inactive in the absence of water, one study suggests that the application of ethanol is a potential mechanism for increasing the longevity[212,250] and durability[274–276] of resin-dentin bonds. However, several authors indicate that ethanol wet bonding yielded higher immediate bond strengths and resulted in lower nanoleakage in root canals.[237,246] Although there are differences in the suggested protocol in regard to concentration and time of application, a recent study suggested a simple higher concentration (50%) of ethanol for 60 seconds.[266] Others indicate that using a high-intensity light-curing unit and/or increasing the irradiation time for the adhesive systems and resin cements will improve the adhesion of these systems to the canal wall dentin.[228,230,244,249] One paper indicated that increasing the light-curing time improved bond strengths to root dentin.[229]

A myriad of studies suggests methods and materials for increasing the longevity of hybridization by improving the resistance of collagen fibrils to enzymatic degradation.[207,277,278] Several studies suggest the application of chlorhexidine (CHX) as a protease inhibitor for MMPs[261] and cysteine cathepsins[270] to preserve the hybrid layer from degradation. Furthermore, several studies indicate that a 2% CHX or a CHX-containing phosphoric acid for etch-and-rinse adhesive systems may be an excellent method for increasing the long-term stability of collagen fibrils in the hybrid layer by inhibiting endogenous MMPs and cathepsins.[268,269]

It has been demonstrated that the use of ethylenediaminetetraacetic acid (EDTA) inhibits MMP-2 and MMP-9 when applied for 1 to 5 minutes,[260,272] while one in vitro study indicated an application of EDTA preserved the dentin-adhesive interface.[266] Thus, the use of EDTA has been indicated as a dentin pretreatment for dentin adhesives.[212,266] However, one study demonstrated that prolonged rinsing with water removes the EDTA and there may be no residual EDTA to inhibit the degradation by endogenous MMPs.[260] Several studies indicate that an increase in the extent of cross-linking of the collagen fibrils prior to adhesive application may increase the potential for durability, while other studies indicate that cross-linkers enhance the mechanical properties of these substrates. Cross-linking agents have been purported to have anti-MMP properties,[253,257] thus reducing enzymatic degradation.[273] However, the application time for desirable therapeutic effect is not feasible,[279,280]

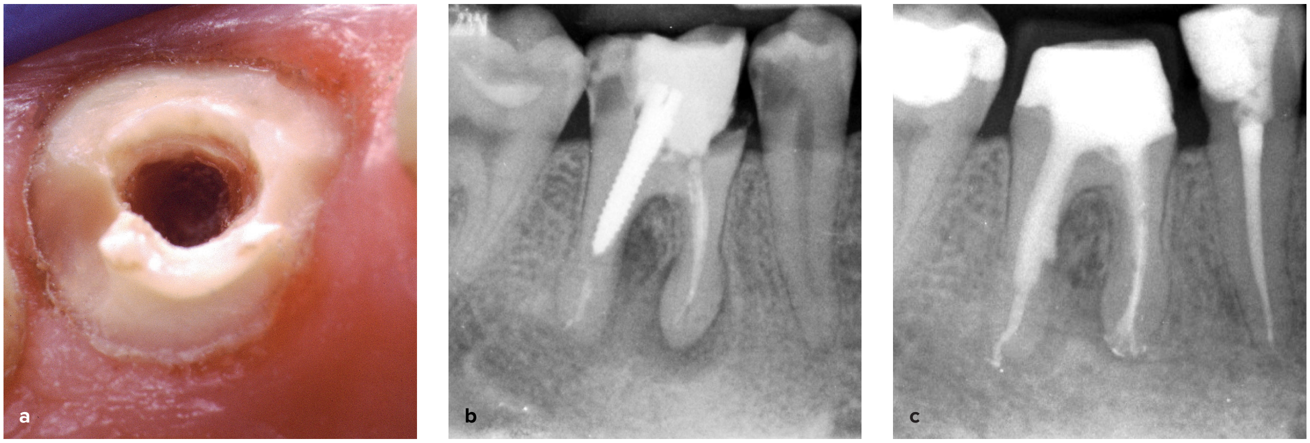


Fig 1-6 *(a)* Overpreparation of the post space to accommodate a larger selected fiber-reinforced post can weaken the remaining tooth structure and increase the potential for root fracture. *(b)* Root perforation caused by improper preparation and placement of an oversized post. *(c)* Repair of the perforation seen in *b*. (Dentistry in *b* and *c* courtesy of Riccardo Tonini, MD, DDS.)

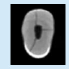
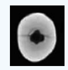
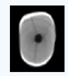
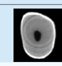
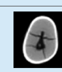
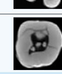
and modification into a simplified protocol using proanthocyanidins incorporated into etchants and adhesives is recommended.[254,256,258,259] Several studies indicate the use of benzalkonium chloride (BAC) or BAC-containing acid or adhesives to inhibit the activity of the endogenous MMPs.[264,271] Because the root canal anatomy can impose limitations to achieving a quality hybrid layer, modified clinical protocols may have positive implications for improving the quality of the adhesive interface and the long-term adhesion of fiber-reinforced post systems to dentin. This in turn can improve the structural integrity of the remaining radicular dentin and increase the retention and resistance to displacement[55,168,281] while dissipating and reducing functional stresses along the entire adhesive interface, thus providing maximum post retention and core stability.

Conservation of tooth structure

Numerous in vitro studies support evidence that conservation of sound tooth structure is the most important factor to the successful management of structurally compromised ETT.[47,51,216,282–288] It is well supported in the literature that the longevity of an ETT is directly related to the amount of remaining sound tooth structure.[29,43,289] However, traditional-cast post systems and prefabricated post systems often require the removal of undercuts for a proper path of insertion and adaptation to the canal wall. This enlargement of the post-endodontic channel throughout biomechanical preparation during and after the endodontic procedure removes dentin during cleaning and shaping of the canal. The removal of additional dentin to accommodate placement of a larger post diameter significantly weakens the remaining tooth structure[175,285,290] (Fig 1-6). This widening of the canal decreases the thickness of the root wall, which can lead to a diminished wall stiffness that results in increased stress levels[291,292] and can compromise long-term success.[293,294] It is widely accepted that 1 mm of dentin wall thickness is required to prevent root fracture and to properly support the core.[159,295]

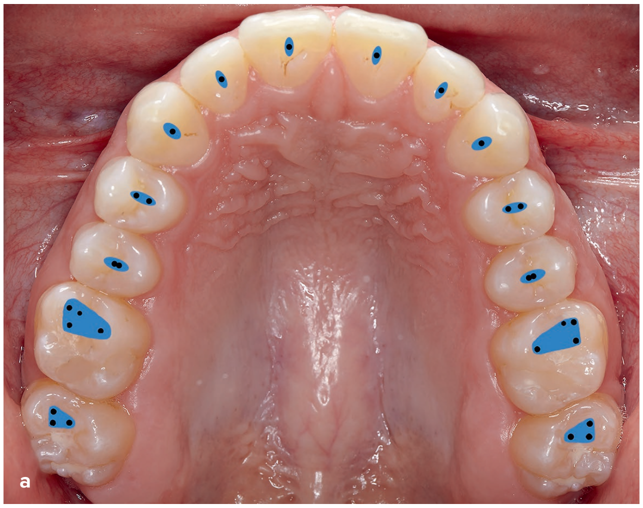
Additionally, during post channel preparation, the preservation of 4 to 5 mm of gutta-percha is necessary to provide an adequate apical seal.[201,296–307] Several techniques for preparing the post channel and the effect of each technique on the apical seal have been investigated and include the use of rotary instruments, heated instruments, and solvents.[175,299,304,308–310] An improper access preparation with too wide an enlargement when performing endodontic therapy can result in an excessive loss of sound coronal

Table 1-1 General guidelines for post placement[300,337–339]

Tooth type	Number of roots/canals	Anatomical root canal variations*	Cervical cross section	Preferred root canal for post channel placement	Cervical cross-sectional shape of the preferred canal
Central incisor					
Maxillary	One root, one canal	99.4%		Main single canal	Circular, ovoid
Mandibular	One root, one canal	73.6%		Main single canal	Ovoid, ribbon-shaped
	One root, two canals	26% incidence of second canal usually lingual to the main canal			
Lateral incisor					
Maxillary	One root, one canal	93.4%		Main single canal	Circular, oval, or ovoid
Mandibular	One root, one canal	71.8% broad buccolingually and narrow mesiodistally		Main single canal	Ovoid, ribbon-shaped
	One root, two canals	28.1% incidence of second canal usually lingual to the main canal			
Canines					
Maxillary	One root, one canal	96.5%		Main single canal	Oval
Mandibular	One root, one canal	94.8%, 89.4% (10.6% incidence of second canal usually lingual to the main canal)		Main single canal	Ovoid
First premolars					
Maxillary	One root, one canal	52.2%, 21.3%		Main single canal	Round, ovoid
	Two roots, two canals	46.7%, 75.8%; mesial developmental root depression; root concavities are present on both mesial and distal surfaces of the root		Palatal root	
	Three roots, three canals	1.15%, 1.4%			
Mandibular	One root, one canal	97.9%, 72.2%		Main single canal	Ovoid
Second premolars					
Maxillary	One root, one canal	90.7%, 50.3%; developmental depressions are often present on the mesial and distal aspects of the root		Main single canal	Ribbon-shaped, elliptical
Mandibular	One root, one canal	99.6%, 91.1% (8.9% incidence of second canal)		Main single canal	Ovoid
First molars					
Maxillary	Three roots, three canals	95.9%; mesiobuccal 42.9%; two mesiobuccal canals 57.1%; distobuccal 98.3% (only variation in mesiobuccal canal)		Palatal root	Circular, ovoid
Mandibular	Two roots, three canals	85.2%; two mesial canals (100%); distal root one canal (68.3%)		Distal root	Ovoid
Second molars					
Maxillary	Three roots, three canals	88.6%; mesiobuccal 52.9%; distobuccal (99.7%); palatal (99.9%)		Palatal root	Circular, ovoid
Mandibular	Two roots, three canals	76.2%; two mesial canals (86%); one distal (85.1%)		Distal root	Elliptical, C-shaped
	One root	C-shaped (8.5%) and single conical roots (8.3%)		Main single canal	C-shaped

This table indicates anatomical root canal variations in Asian and non-Asian populations. However, anatomical variations exist in different subpopulation groups. The table provides the necessary information for post preparation and placement. During post channel preparation, the preservation of 4 to 5 mm of gutta-percha is necessary to provide an adequate apical seal.[201,296–307]

*If there are two numbers, the first number is the prevalence for that number of roots for a given tooth, and the second number is the prevalence for that number of canals for said tooth among the population groups studied.



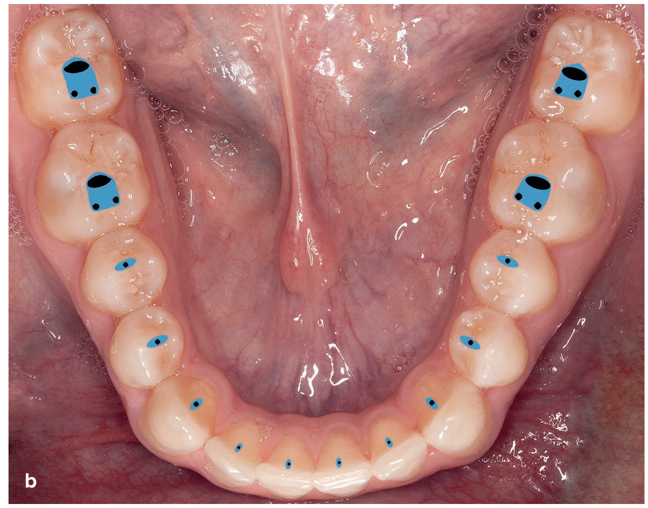


Fig 1-7 *(a and b)* Conservative endodontic access openings.

tooth structure[20,40,311,312] and increase the occurrence of fractures[43,206,291,313] (Fig 1-7). In addition, endodontic access on a tooth with loss of one or both marginal ridges increases the potential for fracture.[29,44,314–317] Investigators have reported that rotary instruments caused more dentinal defects, such as craze lines and partial cracks, which have the potential to develop into fractures after endodontic and restorative treatment.[318–320] However, no defects were observed with hand file instrumentation.[318] Furthermore, overpreparation of the post space and the utilization of larger posts decrease the resistance to fracture.[51,285,287] This reduction in the amount of dentin weakens the structural integrity of the tooth[216] and can be responsible for horizontal and vertical root fracture.[291,321–326] To prevent overpreparation during the endodontic or restorative procedure, it is recommended that the root morphology be considered for each tooth type prior to treatment. Mandibular incisors, maxillary second premolars, and the distal root of mandibular molars have mesiodistal concavities and may be narrower mesiodistally than they appear in the radiograph.[327] A CBCT image can provide a 3D visualization of these anatomical features in cross section and reduce the potential for a weakened structural integrity or root perforations[328] by providing a view of the tooth anatomy. Because of the wide range in anatomical variation in regard to number and shape of roots and root canals for each tooth type,[329–335] a comprehensive knowledge of root morphology[179,336] and an understanding of external root anatomy can provide insight for selecting the teeth and roots that are most appropriate for post placement with less potential for thinning and root fracture[300] (Table 1-1; for further information, see section entitled "Guidelines for Restoring the Intraradicular Space"[300,337–339]).

Improvements in composite materials, adhesive technology, and endodontic procedures and technology have resulted in a more conservative design concept.[9] This minimally invasive concept preserves intact tooth structure, reducing the potential for failure[209] while providing adequate retention and resistance form for the final restoration.[40]

One method of the direct fiber-reinforced resin post system (see section entitled "Direct Fiber-Reinforced Post and Core System") allows preservation of the canal structure and can be utilized in the treatment of irregular canal configurations. This procedure does not require a converging path of insertion and can be used with minimal preparation

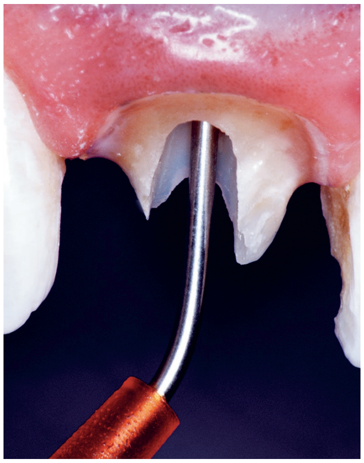


Fig 1-8 A dual-cured composite or resin cement was injected into the post channel with a needle-tube syringe. It is important to place the tip to the base of the channel and inject slowly while removing the tip slowly.

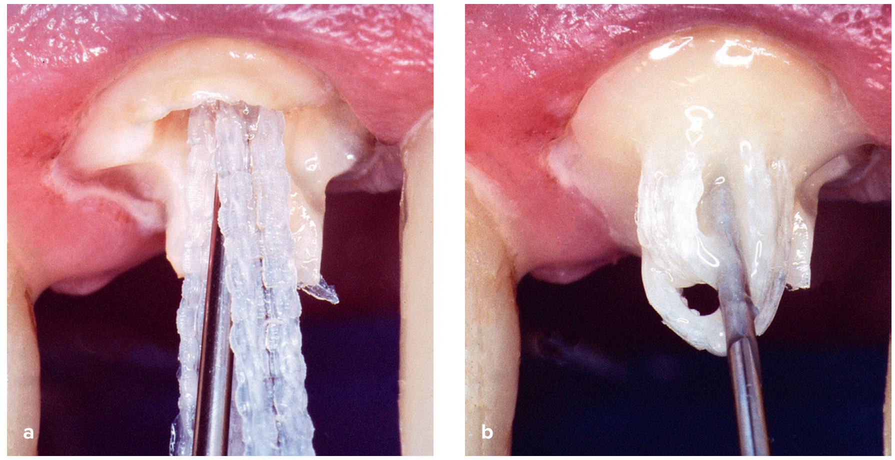


Fig 1-9 *(a and b)* The intraoral fabrication of a direct fiber-reinforced post using a plasma-coated fiber ribbon. After the adhesive protocol and injection of a dual-cured resin cement, the fiber is immediately inserted into the posthole with a modified Luk's gutta-percha condenser, and the fiber is folded over so that the ends are pointing back into the post channel and between the emerging ends of the fiber. This method allows preservation of the canal structure and can be utilized in the treatment of irregular canal configurations.

because it utilizes the undercuts and surface irregularities to increase the surface area for bonding (see Fig 1-9). This conservation of dentin reduces the possibility of tooth fracture during function or in the event of traumatic injury.[287]

Internal adaptation

Conventional luting cements such as zinc phosphate only fill the void between the restorative interfaces without attaching to either surface.[55] Dual-cured resin luting agents mechanically and chemically interact with the resin of fiber-reinforced composite resin posts and the dentin, which bonds and seals the adhesive interface. Previous methods of cementation have been investigated that include placement of the cement onto the post and/or placing the cement with paper points, an endodontic explorer, and lentulo spiral.[175,340,341] The lentulo spiral was considered the superior method of placement, providing a uniform thickness of cement with no voids.[341] The author prefers placement of the adhesive resin cement onto the post and injection of the material with a needle tube placed at the base of the prepared post space, slowly removing the syringe tip to prevent the formation of air voids[196] (Fig 1-8). The use of composite resin cements between the adhesive system and the reinforcement material ensures a more intimate contact with the dentin bonding agent because of lower viscosity that results in enhanced adaptation.[342] One study claims that low–elastic modulus composite acts as an elastic buffer that compensates for polymerization shrinkage stress by flow, minimizing gap formation and reducing microleakage[343]; however, there is no evidence that flowable-lined composite restorations have improved margins or reduced leakage. If the elastic modulus is low, the composite will flex as the tooth bends, thus minimizing fracture. Also, lower-viscosity resin cements enhance post and dentin wetting, improving the interfacial internal adaptation and reducing void formations that contribute to reduced post retention and increased microleakage.[344] Therefore, the use of a resin luting cement to line and strengthen the canal walls actually reinforces the root and supports the tooth-restorative complex[166,345] (Fig 1-9).

Optimal esthetics

When esthetics is of primary concern, the selection of appropriate restorative materials becomes an important consideration. The purpose of selecting tooth-colored posts for enhancing esthetics in ETT is to aid in the creation of a natural-looking restoration. An esthetic post prevents the dark showthrough that so often is observed with a metal post.[346] The light-transmission properties of traditional prefabricated or cast-metal posts differ from natural teeth where light is reflected, absorbed, or transmitted through the tooth. The incidental light is completely blocked by the metal post, which causes the characteristic shadow at the submarginal zone.[347] When using an all-ceramic restoration, the color and opacity of the metal post may lead to discoloration and shadowing at the gingiva and cervical region of the tooth.[173,348]

The secondary optical properties (eg, translucency, opacity, opalescence, iridescence, and fluorescence) of the composite allow light to pass through the natural tooth and the restorative material to reflect, refract, absorb, and transmit according to the optical densities of the hydroxyapatite crystals, enamel rods, and the dentinal tubules.[349] Composite fiber-reinforced post systems made of quartz and glass provide these secondary optical properties for reproducing the various optical characteristics that are observed through the enamel and the dentin.[42,173] Therefore, in creating optimal esthetic harmony with the surrounding dentition, the underlying restorative material directly influences the final restoration (Fig 1-10; for more information, see chapter 3).

Resistance to catastrophic root failure

Root fracture is another reason for failure of the post and core system.[127,152,164,184] The primary goal of restoring ETT is to develop a design that distributes occlusal stress uniformly while preserving the tooth structure if the restoration fails during occlusal stress or dental trauma. Traditional cast posts (ie, stainless steel, chrome cobalt) have a modulus of elasticity as high as 10 times greater than that of natural dentin[55,350]; however, an exception is titanium. This possible incompatibility can create stress concentrations in the less rigid root, resulting in post separation or failure.[170–172,206,351–353] Additionally, the transmission of occlusal forces through the metal core can focus stresses at specific regions of the root and have been implicated in the high incidence of vertical root fracture[55,185,354] (Fig 1-11). The fiber-reinforced composite post consists of fibers embedded in a polymeric matrix, and this combination creates a stiffness behavior for the post system that is similar to root dentin (elastic modulus of 18 GPa), which preserves the natural flexibility of the tooth. In addition, this similarity in elastic modulus between the fiber post and dentin reduces stress concentrations and restores stress distributions that are similar to the sound tooth.[185] In the sound tooth, stress is more uniform.[20,355,356] Because fiber posts exhibit a modulus of elasticity similar to that of root dentin,[206,357] the applied forces are more evenly distributed along the length of the post,[206,358] which minimizes the stress concentrations and reduces the potential risk for catastrophic root fracture.[29,95,206,359–366] Numerous stress analysis studies conclude that ETT restored with fiber-reinforced composite posts have lower and more favorably distributed stresses than do teeth with metal posts.[111,355,367–372] Therefore, the fiber-reinforced composite post has a negligible incidence of root fracture[118,201,356,361,373,374]; however, only laboratory tests show a difference in root fracture when metal or zirconia posts are used compared to fiber posts. The adhesive interface with different elastic moduli, such as with a metal post system and dentin, represents the weakest point of the restorative system.[351,356,375,376] Thus, fiber posts with mechanical properties similar to root dentin induce lower stresses than metal posts at the interface,[114,206] and their clinical performance is considered more favorable because of their favorable fracture mode[69,201] and reduced root fracture.[361,365,377–379]

Fractures in ETT with fiber-reinforced posts usually occur in the cervical region, whereas metal posts have demonstrated a more apically positioned fracture.[111,361,362,366,379] One study of different post systems reported that teeth restored with posts had properties similar to those of sound tooth structure. Glass fiber posts demonstrated favorable

Fig 1-10 *(a to f)* A comparison of a metal-ceramic crown with metal post and the same tooth with a direct fiber-reinforced post with all-ceramic crown. The incidental light is completely blocked by the metal substructure of the metal-ceramic crown and the metal post, causing the characteristic shadow at the submarginal zone. Notice the improved light transmission of the restored tooth with the direct fiber-reinforced post system and all-ceramic crown as well as the improved color of the soft tissue.

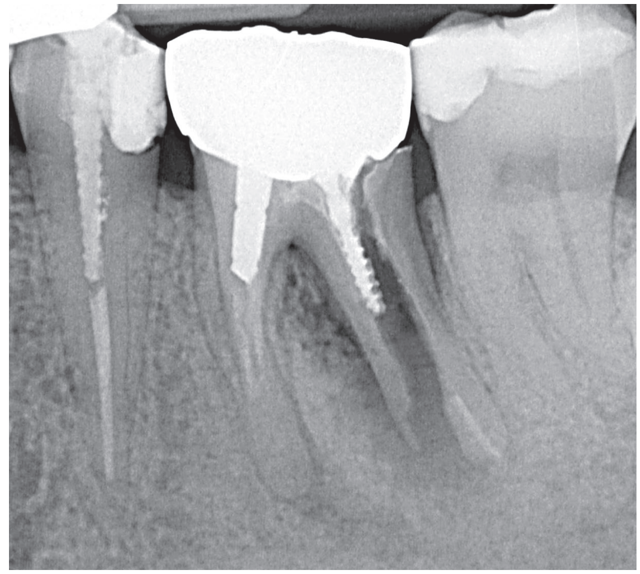


Fig 1-11 Vertical root fracture in a mandibular first molar resulting from stresses caused by occlusal forces through the metal core of the post.

fractures, whereas those restored with zirconia and titanium posts demonstrated catastrophic fractures.[353] Those that were considered favorable fractures exhibited failure patterns that allowed for endodontic retreatment and/or repreparation[380] of the existing restored tooth and occurred more frequently in the cervical third.[356,381,382] Also, studies indicate that dentin-bonded resin post-core restorations provided significantly less resistance to failure than the cemented custom-cast post and core and that the dentin-bonded resin post and core fractured in every instance before the roots fractured.[383]

Furthermore, an important factor in the structural design is the fail-safe feature that allows retrievability of the fiber-reinforced composite post. Unlike ceramic post systems, this material is less difficult to remove from the canal with a low- or high-speed diamond bur or an ultrasonic instrument for endodontic and/or restorative retreatment[42,384,385] without the risk of root perforation. One study reported that fractures occurring with the use of glass fiber or quartz posts were repairable, whereas fractures that occurred with titanium or zirconia posts were irreparable.[353] Therefore, significant factors that affect resistance to root fracture should be considered, such as the biomechanical behavior of the material, occlusal stress patterns, eliminating stress at the interface of components of the system,[44] preservation and protection of tooth tissue, and the use of an adhesive design concept. Additionally, forces that act on endodontically treated restored teeth can cause failure during mastication.[54]

Differences in the biomechanical behavior of anterior and posterior teeth should be considered due to the different force directions each receive.[386,387] Posterior teeth receive compressive loads that are vectored in an occlusogingival or vertical direction, whereas anterior teeth receive flexural stresses that are vectored in a horizontal or lateral direction.[69,388,389] Masticatory loads usually generate compressive stresses, while fatigue fractures are generally caused by tensile stresses and not compression.[45,125,201] These lateral tensile stresses generally are more destructive to the tooth-restorative interface and occur in the anterior region.[69,377] Therefore, consideration should be taken of the occlusal scheme (ie, canine or group function, type of occlusion, overjet and overbite) according to tooth location to determine the potential risk for failure. Horizontal forces generated by parafunction may increase the risk of failure to ETT.[388,389] To minimize the magnitude of stresses, the occlusal design should allow occlusal points of contact while minimizing wider areas of contact.[388,390,391] Furthermore,