Jorge Perdigão
Editor

Restoration of Root Canal-Treated Teeth

An Adhesive Dentistry Perspective

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Preface

I have read some dentistry books in which the respective authors describe how daunting it is to write a book that involves so many different coauthors. Yet, writing this book was not a very difficult task. I am fortunate to have known so many talented colleagues who accepted my challenge to write the book chapters. Although they come from different countries with different dental education philosophies, such as Brazil, Canada, Finland, Germany, Portugal, South Korea, and USA, they all speak the same common “dental” language.

I have taught clinical dentistry to undergraduate students continuously since 1985, the year I finished dental school. The idea to write this book has been fermenting in my mind inspired by the need to teach evidence-based concepts on the restoration of endodontically treated teeth to our dental students at the University of Minnesota, as well as to colleagues who attend my lectures around the world. The conceptual blueprint behind the book was far from writing an encyclopedia on the topic of the restoration of endodontically treated teeth. Our goal was to compile the perspectives from experts in the this particular subject on the different aspects that involve the diagnosis, treatment planning, material properties, clinical procedures, and longevity of restored endodontically treated tooth. The ultimate goal was to help clinicians make decisions based on the available evidence.

We all hope that you will enjoy this book.

Minneapolis, MN, USA Jorge Perdigão

Acknowledgments

To all of those who helped me during my 40-year-long career in Portugal, USA, and Belgium, I am grateful for everything that I have learned from you. Among those, I must leave here my everlasting appreciation to the late Prof. Humberto Ferreira da Costa, one of my mentors at the University of Lisbon Dental School.

I am eternally grateful to my father Adelino and my mother Arlete for their humbleness, honesty, and extreme hard work, which made it possible that I became the first member of my family to finish secondary education or high school.

I am grateful to my colleagues Dr. Andressa Ballarin and Dr. Guilherme C. Lopes for their exceptional design skills. Besides being a full-time dentist and mother, Andressa found time to draw Figs. 1.1 and 1.2.

Last, but not the least, special thanks to my colleagues Dr. Ana Sezinando and Dr. Elen Borges.

We never quit.

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Endodontic Considerations for the Restoration of Endodontically Treated Teeth

1

Brian D. Barsness and Samantha Harris Roach

Abstract

The aim of this chapter is to offer a guide, from the endodontist's perspective, as to how root canal-treated teeth should be restored, and to give some clinical recommendations to help meet these restorative goals. The endodontic and restorative components of treatment are typically considered as independent phases. However, when considering the impact of each of these phases on the long-term prognosis of the tooth, it becomes apparent that both the endodontic and restorative plans should be considered jointly before treatment is carried out. With so many options for the timing of treatment, endodontic and restorative materials, and restoration design, the clinician is left with some difficult decisions at the treatment planning phase. In this chapter, considerations for the material characteristics, restoration design, and management of post placement complications are presented and discussed with respect to their impact on long-term prognosis. In addition, treatment sequencing, techniques of temporization, and strategies to prevent coronal microleakage of endodontically treated teeth are discussed in detail.

1.1 Introduction

The objectives of nonsurgical endodontic therapy have been described classically as being twofold: biological and mechanical. The biological objectives of endodontic therapy are focused on removing diseased and infected tissues, as well as eliminating bacterial products such as endotoxins, from the canal system. The successful

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outcome of healing and function, ultimately, depends upon maintaining the coronal and apical seal of the endodontically treated tooth.

Similarly, when determining the long-term prognosis for a tooth requiring endodontic therapy, it has been suggested by the results of several studies (Ray and Trope 1995; Gillen et al. 2011) that the quality of the coronal restoration after endodontic therapy may be as important as the quality of the endodontic treatment itself. These studies highlight the importance of coronal restoration after endodontic treatment. It follows that the plan for the definitive occlusal restoration should ideally be established at the time the endodontic therapy is planned. The question then arises of how these endodontically treated teeth are best restored.

Although there has been a recent trend in endodontic research to promote conservative access and canal preparation (Krishan et al. 2014), the fact remains that some loss of tooth structure does occur even with conservative endodontic treatment techniques. Additionally, the materials used during root canal therapy may also play a role in decreasing the integrity of dentin (White et al. 2002). And in many cases, teeth requiring endodontic therapy present with preoperative tooth structure loss due to caries or previous restorations, thereby adding complexity to both the endodontic and restorative phases of treatment.

The aim of this chapter is to offer a guide, from the endodontist's perspective, as to how root canal-treated teeth should be restored, and to give some clinical recommendations to help meet these restorative goals.

1.2 How Does the Coronal Restoration Impact the Success of Endodontic Treatment?

It is generally accepted that a favorable outcome of endodontic treatment relates to the technical quality of the canal disinfection and long-term seal of the obturating material. Several prospective outcome studies (Marquis et al. 2006) have presented an expected favorable outcome for primary root canal therapy at above 90 % in the absence of preoperative apical periodontitis and approximately 80 % in the presence of preoperative apical periodontitis. These favorable outcomes decrease dramatically in the presence of inadequate root canal fillings and apical periodontitis (de Chevigny et al. 2008).

Although an adequate coronal seal may be provided by a well-obturated root canal system, over time an inadequate coronal restoration may allow for the ingress of microbes and contribute to the recontamination and ultimate failure of the endodontic and restorative treatment. There has been debate regarding the priority of impact regarding such an outcome. Which is more important; an adequate endodontic treatment or an adequate coronal restoration? Could they be equally important? One early study by Ray and Trope (1995) presented a thought-provoking finding, in that the effect of the restoration on the radiographic success was statistically greater than the effect of a good endodontic filling. Adding to the debate, Tronstad et al. (2000) raised the counterpoint, stating that the quality of the root canal filling was the most important factor for the outcome of endodontic treatment. If the quality of the root filling was good, a good restoration improved on the endodontic success rate by more than 10 %. However, if the quality of the root canal filling was poor, the quality of the coronal restoration was of no importance for the outcome of the endodontic treatment.

In a systematic review published by Gillen et al. (2011), the impact of the quality of coronal restoration and the quality of root canal fillings on success of root canal treatment were considered. Their findings gave support to the notion that all aspects of treatment have impact on outcome. The odds for healing of apical periodontitis increase with both adequate root canal treatment and adequate restorative treatment. Poorer clinical outcomes may be expected with adequate root filling-inadequate coronal restoration and inadequate root filling-adequate coronal restoration. There seemed to be no significant difference in the odds of healing between these two combinations.

It is difficult at best to understand the risk of unfavorable outcomes where there exists such variation in treatment protocols and outcome measures. Large, epidemiological studies can be useful in assessing cohorts to better interpret clinical decision making and outcomes. One such study by Salehrabi and Rotstein (2004) retrospectively evaluated the records of 1,126,288 patients having received an initial endodontic treatment over a period of 8 years. Over this 8-year follow-up period, 97 % of teeth treated by nonsurgical root canal therapy were retained in the oral cavity. Of the teeth requiring extraction, 85 % did not have a permanent crown placed.

So, while it becomes imperative to provide a permanent restoration on the endodontically treated tooth, is there an expected rate of unfavorable outcome associated with prosthodontic failure? Vire (1991) evaluated and classified failures of endodontically treated teeth according to prosthodontic, periodontic, and endodontic categories. Teeth that had been crowned had a greater longevity (87 months) than uncrowned teeth (50 months). Interestingly, of the 116 endodontically treated teeth, 59.4 % were prosthetic failures, primarily due to crown fracture.

Further adding to the complexity of restorative considerations, Iqbal et al. (2003) performed a retrospective analysis of factors associated with the periapical status of restored endodontically treated teeth. The benefit and uniqueness of this study were that the authors explored possible associations between prosthodontic, occlusal, endodontic, and periodontal factors with the apical health of endodontically treated teeth. Three factors were significantly associated with the presence of an apical radiolucency: confirmed occlusal contact, by virtue of the tooth being involved in group function or the only contact in working side and protrusive movements, and endodontic filling and crown margins of poor quality. Good-quality endodontic filling and crown margins improved endodontic outcome. However, occlusal contact was shown to be associated with failing endodontic treatment, thereby increasing the range of factors that may influence endodontic outcomes.

In support of the considerations of permanent restoration, restorative material, and tooth position, Ng et al. (2010) performed a prospective study on the factors affecting outcomes of nonsurgical root canal treatment. This study evaluated tooth survival following primary and secondary root canal treatment. Five hundred seventy-two patients receiving primary root canal treatment and 642 patients receiving secondary treatment were followed annually between 2 and 4 years. Survival was determined as the tooth being present and potentially functional at the time of recall, whereas failure was determined to be a tooth that had been extracted. As a result, the 4-year survival following primary and secondary root canal treatment was 95.4 and 95.2 %, respectively. The restorative factors found to increase the chance of tooth loss were restoration with a temporary restoration only, restoration with a cast post and core, lack of two interproximal contacts, and a position as the terminal tooth in the arch.

In summary, the endodontic and restorative treatment complex poses numerous clinical considerations to the clinician. As presented, the significance of both endodontic and restorative measures relies on thoughtful consideration of material science, biomechanical principles, and treatment timeframes. With proper application of these considerations, the restored endodontically treated tooth can be expected to serve its intended function for many years.

1.3 When and Why Do Endodontically Treated Teeth Require Full Coverage?

The need for a full-coverage restoration after endodontic therapy is largely determined by tooth type, amount of tooth structure loss, and the amount of occlusal stress on the tooth.

1.3.1 Anterior Teeth

By an in vitro study, Trabert et al. (1978) found that there was no significant difference in resistance to fracture between untreated anterior teeth and endodontically treated anterior teeth without full-coverage restoration. In a more clinically based retrospective study including 1273 endodontically treated teeth, Sorensen and Martinoff (1984) found that long-term prognosis for anterior teeth, both maxillary and mandibular, was not increased with full-coverage restoration with or without a metal post versus simple restoration of the endodontic access. However, some current research may indicate that bonded fiber posts may offer some reinforcement (for more on this concept, see Chap. 6). In most cases, anterior teeth with small proximal restorations can be restored with lingual resin restorations. To restore these teeth, the gutta-percha should be seared off at or below the level of the cementoenamel junction, and the resin should be placed directly on top of the gutta-percha. In anterior teeth, full coverage may only be necessary when there has been significant loss of tooth structure prior to endodontic therapy or for esthetic reasons.

1.3.2 Posterior Teeth

In the same study by Sorensen and Martinoff (1984), it was found that full coronal coverage did significantly improve the long-term success rate for endodontically treated maxillary and mandibular premolars and molars. The reasoning behind why endodontically treated molars without cuspal coverage have a decreased long-term prognosis can be explained by cuspal deflection. When molar teeth with MO or MOD preparations and endodontic accesses are subjected to occlusal-type forces, the cusps actually move more than intact teeth (Panitvisai and Messer 1995). Even when the marginal ridges are preserved, the adjacent cusps are still significantly weakened (Linn and Messer 1994). This type of cuspal deflection creates stress within the tooth and can lead to catastrophic coronal fractures (Fennis et al. 2002). Based on these findings, it is suggested that all posterior teeth receive full-coverage restorations following endodontic treatment. The only exception to this rule may be the mandibular first premolar. In some cases, when the lingual cusp of this tooth is underdeveloped, it may not be subject to the wedging forces of opposing cusps when restored with an occlusal repair of the endodontic access (Hansen et al. 1990).

1.3.3 Ferrule

If a crown is deemed necessary after root canal therapy, it is also imperative that the dentist considers the amount of tooth structure remaining coronal to the alveolar crest in order to respect biologic width and provide space for a crown margin on tooth structure. The preservation of intact coronal and radicular tooth structure is crucial in optimizing the biomechanical behavior of the restored tooth, by allowing for incorporation of a “ferrule” feature during crown preparation. As stated by Sorensen and Engelman (1990), a ferrule effect is created by incorporating a 360° collar of the crown surrounding the parallel walls of the dentin extending coronal to the shoulder of the preparation. The result is an increased resistance form of the crown from the extension of dental tooth structure (Fig. 1.1).

Restorative considerations for endodontically treated teeth always include maintaining an effective coronal seal, protection of the remaining tooth, and restoration of both function and esthetics. Rosen (1961) defined the concept of extra-coronal “bracing” as a subgingival collar or apron of gold extending as far as possible beyond the gingival seat of the core and completely surrounding the perimeter of the cervical portion of the tooth, serving to prevent fracturing of the root. Rosen and Partida-Rivera (1996) tested this using 76 extracted maxillary lateral incisors restored with gold cervical collars and coronally threaded with a post until fracture occurred. The collar significantly reduced the incidence of root fracture. Libman and Nicholls (1995) reported that an increased ferrule length increased the resistance to fracture, while an increased post length did not. One significant consideration in the ferrule design is the influence of biologic width. Fugazzotto and Parma-Benfenait (1984) stated a minimum of at least 3 mm should be left between the crown margin and the alveolar bone in order to avoid impingement on the coronal attachment of the periodontal connective tissue. In consideration of the restorative dimension then required, at least 3 mm of supra-alveolar tooth structure, in addition to ferrule height, may be required to provide an effective restorative dimension (Fig. 1.2).

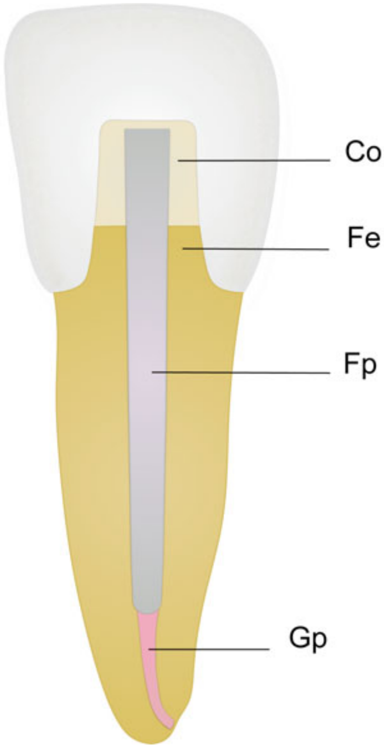


Fig. 1.1 Diagram depicting an endodontically treated tooth restored with a fiber post, a core buildup, and a crown. *Co* core buildup, *Fe* ferrule effect, *Gp* residual gutta-percha, *Fp* fiber post

Occasionally, the clinician may recommend a crown lengthening procedure on a tooth with inadequate coronal tooth structure for an effective ferrule height and adequate biologic width. In some cases, crown lengthening may compromise the supporting bone of adjacent teeth or the crown to root ratio of the tooth in question. Orthodontic extrusion has been presented as a reasonable alternative to crown lengthening in these situations. However, this procedure may require greater length of treatment. With the potential drawbacks of both crown lengthening and orthodontic extrusion, the clinician may need to decide whether or not to include a ferrule around the entire diameter of the tooth. This clinical alternative was evaluated in a literature review of 62 articles by Juloski et al. (2012). Their findings suggest that if the clinical situation does not allow a 360° ferrule, an incomplete ferrule is considered to be better than the absence of a ferrule. Additionally, including a ferrule lowers the impact of the post and core system, luting agents, and final restoration on the performance of endodontically restored teeth. This study also found that orthodontic extrusion lead to a better prognosis than surgical crown lengthening.

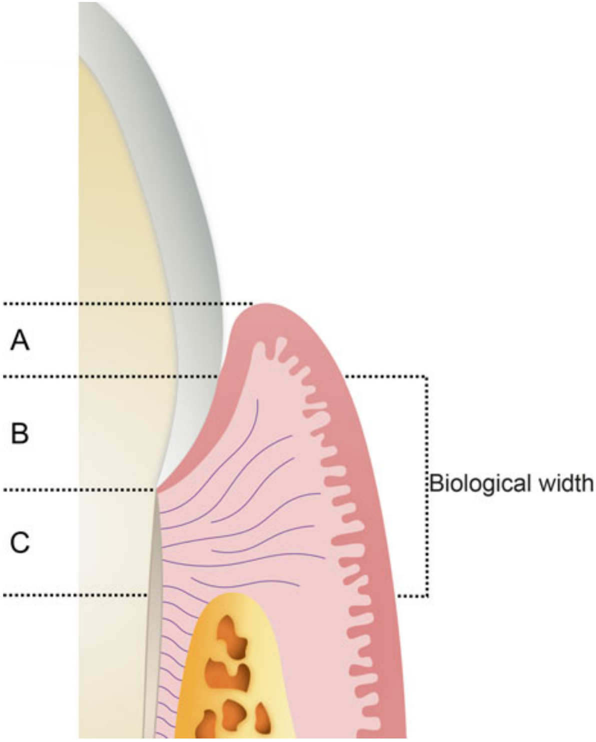
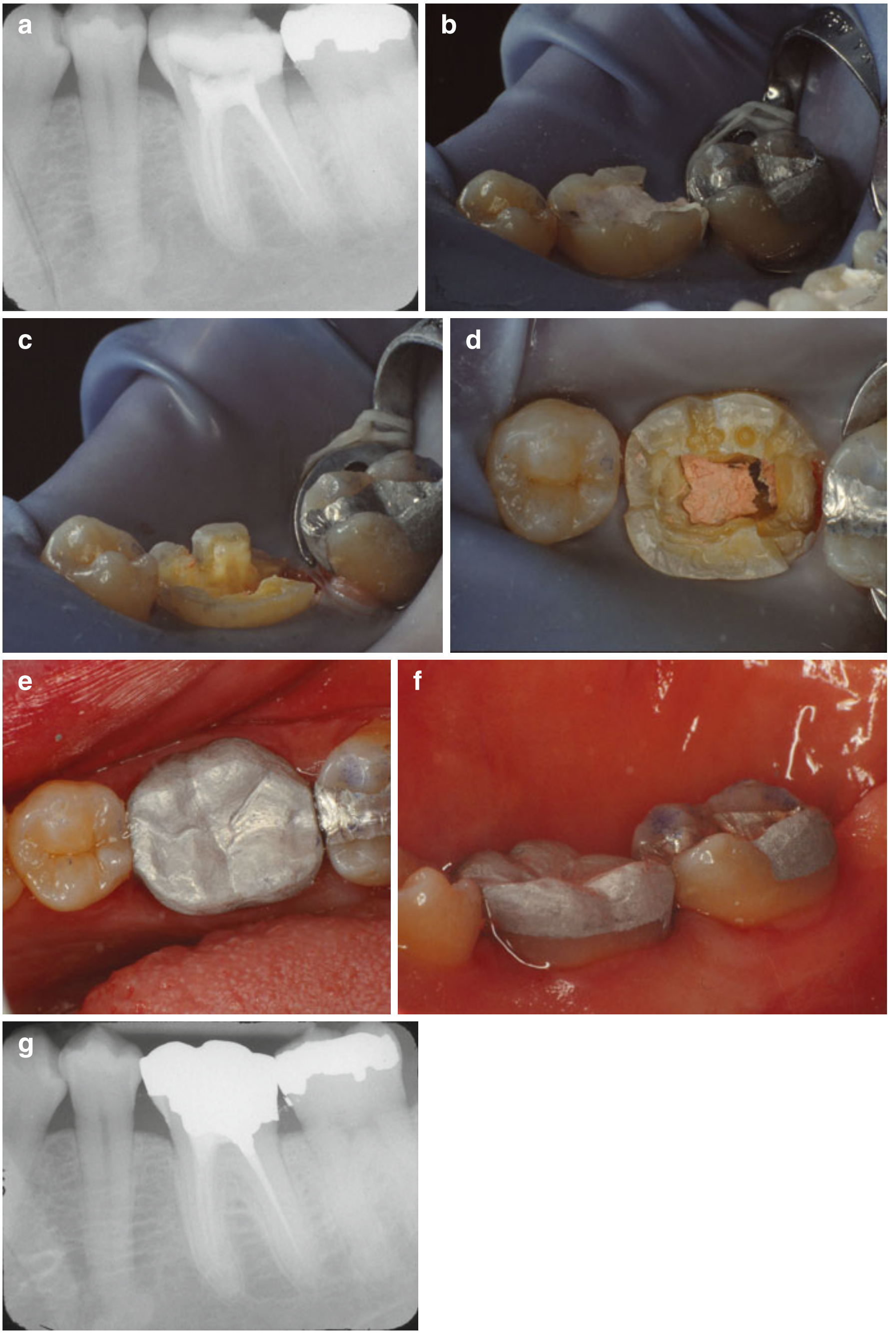


Fig. 1.2 Biological width. *A* Sulcular epithelium, *B* junctional epithelium, *C* connective tissue

1.4 Alternatives to the Ideal Restoration

1.4.1 Cuspal Coverage Amalgam

Although a full-coverage crown is usually the restoration of choice in posterior teeth, a complex amalgam restoration that covers the cusps has been suggested as a suitable alternative (Starr 1990) (Fig. 1.3). This type of restoration may be indicated in cases in which cost of the crown is prohibitive for the patient or if insufficient tooth structure remains coronal to the crest of bone to maintain biologic width and a crown ferrule. With this type of cuspal coverage restoration, all of the remaining cusps are reduced 2 mm and rebuilt with amalgam. It has also been suggested that, if the pulp chamber height is less than 4 mm, amalgam should be condensed 2–4 mm into each canal to increase the fracture resistance of the amalgam restoration (Nayyar et al. 1980; Kane et al. 1990). Although the long-term prognosis for this type of complex amalgam restoration may not be as favorable as a full-coverage crown (Martin and Bader 1997), Mondelli et al. (1998) found that these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cusp-covering amalgam restorations increase the fracture resistance in comparison to endodontically accessed posterior teeth without cuspal coverage. Smales and Hawthorne (1997) also found that complex amalgam restorations had a mean survival rate of 14.6 years. Therefore, this type of restoration can serve as a good intermediate restoration to protect the tooth until the patient can proceed with a crown or crown lengthening if indicated.

1.4.2 Cuspal Coverage Composite

Like the cuspal coverage amalgam restoration, a composite restoration covering the cusps has also been suggested as an alternative to a crown for endodontically treated posterior teeth. In a laboratory study examining the fracture resistance of endodontically treated molars with direct or indirect cuspal coverage composite restorations, Plotino et al. (2008) selectively covered the mesial cusps and restored the mesial marginal ridges. They found that selectively covering cusps did not restore the strength of the cusps to their preoperative state. However, in an ex vivo study on endodontically treated premolars, Mondelli et al. found that restoring all cusps with composite significantly increased the fracture resistance (Mondelli et al. 2009). Therefore, reducing the entire occlusal surface and all cusps 2 mm and restoring the tooth in composite may offer a suitable option for restoring endodontically posterior teeth especially in the premolar region where a metallic restoration may not be as esthetically acceptable. However, a review of the literature indicates that amalgam is superior to composite for posterior tooth restorations in terms of long-term survivability of the restoration (Kovarik 2009). This may again indicate that a cuspal coverage composite may reinforce the strength of the tooth and serve as a good transitional restoration until a crown can ultimately be placed to protect the tooth long term.

Fig. 1.3 Cuspal coverage amalgam (Courtesy of Dr. Scott B. McClanahan, University of Minnesota School of Dentistry). (**a**) Radiographic image showing tooth #19 root canal completed and coronal temporary restoration in place. (**b**) Clinical image showing tooth #19 root canal completed and coronal temporary restoration in place. (**c**) Temporary restoration is removed, occlusal tooth structure is reduced 2 mm, and mesial and distal box preparations are created. (**d**) Occlusal view of tooth preparation for amalgam cuspal coverage. (**e**) Completed amalgam cuspal coverage restoration (occlusal). (**f**) Completed amalgam cuspal coverage restoration (lingual). (**f**) Radiographic image showing amalgam cuspal coverage in place. Note amalgam condensed into distal canal for retention

1.5 What Are the Guidelines and Techniques for Post Preparations?

Once it is decided that a post is indicated, the practitioner must consider the timing of the post placement, the design (length, width, taper, etc.), and the best location to place the post within the tooth in question.

1.5.1 Timing of Post Space Preparation

Sequencing of the restoration of endodontically treated teeth may seem straightforward until one considers implementing provisional treatment steps, all while maintaining the integrity of the coronal and apical seals established during endodontic treatment. One such challenge exists with post space preparation. When a post space is determined to be necessary for restoration of the tooth (Goerig and Mueninghoff 1983), there is considerable debate regarding the timing of post space preparation with respect to coronal microleakage and apical seal. Immediate removal of the coronal sections of the root canal filling may be accomplished using heated pluggers or an electronic thermal tip. Delayed post space preparation, however, may require the use of rotary instrumentation in combination with solvent softeners. Earlier studies by Dickey et al. (1982) suggest that immediate post space preparation significantly increased apical leakage due to inadequate sealer setting time. Portell et al. (1982), however, reported that the removal of gutta-percha was more difficult with delayed post space preparation. They hypothesized that this may have contributed to greater apical leakage with delayed post space preparation than with immediate post space preparation in their study. More recent studies have indicated less apical leakage associated with immediate post space preparation, as well as immediate post and core placement (Demarchi and Sato 2002; Solano et al. 2005). With increased acceptance of contemporary obturation techniques, such as continuous warm gutta-percha backfill and the use of resin sealers, it seems prudent for the restoring clinician to consider immediate post space preparation, rather than delayed, given the convenience and timeliness afforded by these material and techniques.

1.5.2 Post Length

The length of the post space preparation is determined by both the mechanical retention requirements and the need to maintain an adequate root canal filling dimension for an apical seal. In vitro studies using pressurized dye leakage systems have suggested caution is advised when making the assumption that a minimal apical obturation dimension is equivalent to the apical seal obtained with the intact root canal filling (Abramovitz et al. 2001). The authors of these studies reported that a retained apical filling dimension of 5 mm was inferior to that of the intact root canal filling. Additionally, reduction of the fillings to 3 mm resulted in an unpredictable

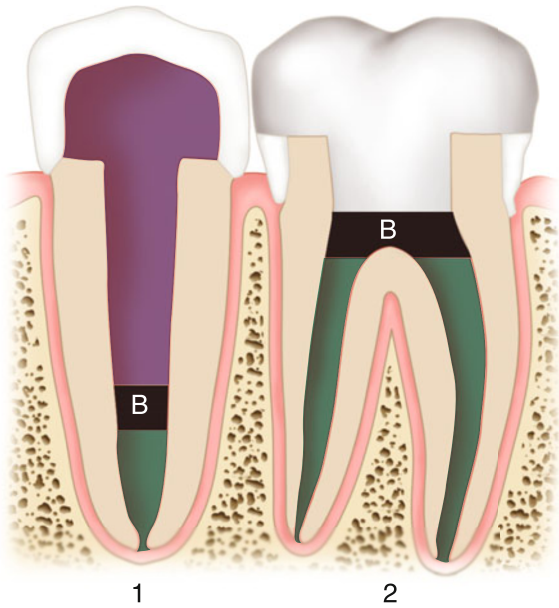

Fig. 1.4 Illustration of intracanal and orifice barriers. (*1*) Represents an endodontically treated tooth restored with a full-coverage crown, post and core, and use of an intracanal barrier (*B*); (*2*) Represents an endodontically treated tooth restored with a cuspal coverage restoration and an orifice barrier (*B*) (Illustration adapted from Mavec et al. (2006))

seal. Portell et al. (1982) found that 7 mm of remaining gutta-percha in the apical fill resulted in less leakage than 3 mm, reaffirming the need to maintain an adequate apical dimension of root canal filling material.

Occasionally, one is confronted with the dilemma of a short crown-root ratio potentially limiting the apical filling dimension as a compromise to maximizing post length retention form. A novel approach presented by Mavec et al. (2006) incorporates the use of an intracanal glass ionomer barrier to assist in the resistance to microleakage resulting from an inadequate dimension of apical filling material. In this in vitro study, for teeth requiring a post and core that allowed for only 3 mm of remaining gutta-percha, a 1 mm glass ionomer barrier placed over the remaining gutta-percha reduced the risk of recontamination of the apical filling material (Fig. 1.4).

In addition to maintaining adequate apical canal filling dimensions, another post length consideration relates to the influence of post fit or "form-congruence" as presented by Schmage et al. (2005). This concept of form-congruence aims to maximize adaptation of the post to the surrounding root canal walls, in order to facilitate stress distribution along the canal wall. This effect was observed in studies by Sorensen and Engelman (1990) with tapered cast post and cores and crowns luted with zinc phosphate cement. This was not, however, observed with parallel-sided posts and post space preparations. There may be an effect of destabilization by creating a post space that transforms a naturally conical canal space into a cylindrical form. Kishen et al. (2004) have suggested that not only the thickness of the dentin wall stabilizes the root but also the presence of inner dentin with a lower elastic modulus than the more mineralized outer dentin. This is particularly important when large diameter post space preparations are created to transform an oval canal into a cylindrical form for the purpose of circumferential post fit, thereby removing critical dimensions of inner dentin. Selecting a post that closely approximates the existing canal form preserves the inner dentin and elastic modulus but may be associated with poor form-congruence. Büttel et al. (2009) reported that the fracture resistance of teeth restored with fiber-reinforced composite posts and direct resin composite crowns without ferrules was not influenced by post fit within the root canal, irrespective of the post length. This implies that excessive post space preparation aimed at producing an optimal circumferential post fit is not required to improve fracture resistance of the root.

1.5.3 Post Placement Complications and Management

Although posts may be indicated in certain clinical situations, the creation of the post space adds a certain degree of risk to the restorative procedure. These risks include contamination of the root canal system, root perforation, and weakening of root dentin leading to vertical root fracture, all of which can affect the long-term prognosis for the tooth.

An important factor in root fracture subsequent to post placement is the reduction of root dentin thickness during post space preparation (Hunter et al. 1989). In a clinical study, Cohen et al. (2003) found that 91 % of diagnosed vertical root fractures were due to inadequately designed posts (either too wide or too long), indicating that the thickness of root dentin had been overly reduced. Therefore, it is important that when creating a post space, the practitioner is as conservative as possible with the removal of dentin to prevent the root weakening due to canal over-enlargement (Tjan and Whang 1985). Using solvents, such as chloroform or heat to remove gutta-percha, will facilitate creating a post space without removing additional dentin or affecting the apical seal as compared to rotary removal techniques (Grecca et al. 2009). However, there is evidence that chloroform, and other solvents used to soften gutta-percha (halothane or xylene), may decrease the microhardness of dentin (Rotstein et al. 1999). Therefore, heat may be the safest way to remove gutta-percha for post space preparation, as long as the practitioner is mindful of the possible damage heat can produce on the supporting tissues if the temperature on the external root surface is significantly raised (Eriksson and Albrektsson 1983). Generally, however, electronic heat sources are safe to use within the canal at temperatures of around 200 °C (Silver et al. 1999) and with short (4 s) intervals of heating (Buchanan 2007).

When the canal space has already been subject to overenlargement either by iatrogenic error or by a previous provider, it may be possible to reinforce the root dentin by using a resin-reinforced dowel system (Saupe et al. 1996). By this method, a smooth light transilluminating post is placed into the overenlarged canal space, and resin is compacted around it against the canal walls. The resin is cured by transmitting light through the post pattern. The post pattern is then removed, the post space is refined within the cured resin, and a permanent post is cemented. Saupe et al. (1996) found this technique to increase fracture resistance in endodontically treated thin-walled teeth. There is evidence, though that this strengthening effect may be reduced over time with occlusal forces and as the bond between the dentin and the resin weakens (Heydecke et al. 2001). For more on this technique and concept, see Chap. 5.

When post-preparation burs are misdirected away from the canal space or when large post drills are used in areas of thin root dentin, there is risk that the post drill can perforate the root dentin and create a communication between the canal space and the external surface of the root (Fig. 1.5). In a radiographic study, Kvinnsland et al. (1989) observed that more than half of the perforations noted in their cases were attributed to post-preparation procedures. The main complication that arises from perforations is the potential for secondary inflammatory periodontal involvement and loss of attachment, eventually causing tooth loss (Wong and Cho 1997). Bacterial infection originating either from the root canal or the periodontal tissues, or both, prevents healing and brings about inflammatory reactions in the tooth-supporting tissues. Conditions such as suppurations, abscesses, sinus tracts, and bone resorptive processes may follow (Tsesis and Fuss 2006). It follows that the goal of repairing a perforation is to achieve a tight and permanent seal that will prevent bacteria and their by-products in the root canal from entering the surrounding periodontal tissues. As far as prognosis for the repair of perforations, the chance of healing of the supporting tissues is improved if the perforation is small, if it occurs below the level of the bone, and if it is repaired immediately under aseptic conditions, preventing bacterial contamination (Fuss and Trope 1996).

Materials that have been used to repair perforations include amalgam (Benenati et al. 1986; Balla et al. 1991), gutta-percha (Petersson et al. 1985; Benenati et al. 1986; Kvinnsland et al. 1989), tricalcium phosphate (Sinai et al. 1989; Balla et al. 1991), zinc oxide eugenol (Bramante and Berbert 1987), Super EBA (Bogaerts 1997), dentin chips (Petersson et al. 1985), Cavit (Sinai et al. 1989), hydroxyapatite (Balla et al. 1991), glass ionomer cement (Fuss et al. 2000), and mineral trioxide aggregate (MTA) (Holland et al. 2001). Currently MTA is widely used as a perforation repair material due to results of in vitro studies demonstrating its sealing ability (Nakata et al. 1998; Daoudi and Saunders 2002) and biocompatibility (Hakki et al. 2012) and case reports demonstrating its clinical success in these types of repairs (Arens and Torabinejad 1996; Main et al. 2004; Mente et al. 2010). Biodentine (Septodont, USA) is a calcium silicate-based material that has been recently advocated as another root perforation repair material. Although in vitro studies have shown Biodentine to exhibit biocompatibility (Mori et al. 2014), there is a lack of evidence supporting its clinical success as a perforation repair material at this time (Malkondu et al. 2014). Another recently introduced perforation repair material is Endosequence Root Repair Material (ERRM). Initial investigations have suggested that ERRM may offer a seal superior to that created by MTA (Jeevani et al. 2014) and provide a similar biocompatibility (AlAnezi et al. 2010). Yet again, there are few clinical cases or long-term clinical studies that have been published using this material as a perforation repair material. Therefore, clinical success and long-term prognosis associated with ERRM are unknown at this time.

In some cases, especially in large perforations, it may be difficult to avoid pushing repair materials beyond the root and into the periodontal ligament space, possibly changing the architecture of the supporting structures and impairing the healing process. In these cases, the use of an internal matrix using a biocompatible

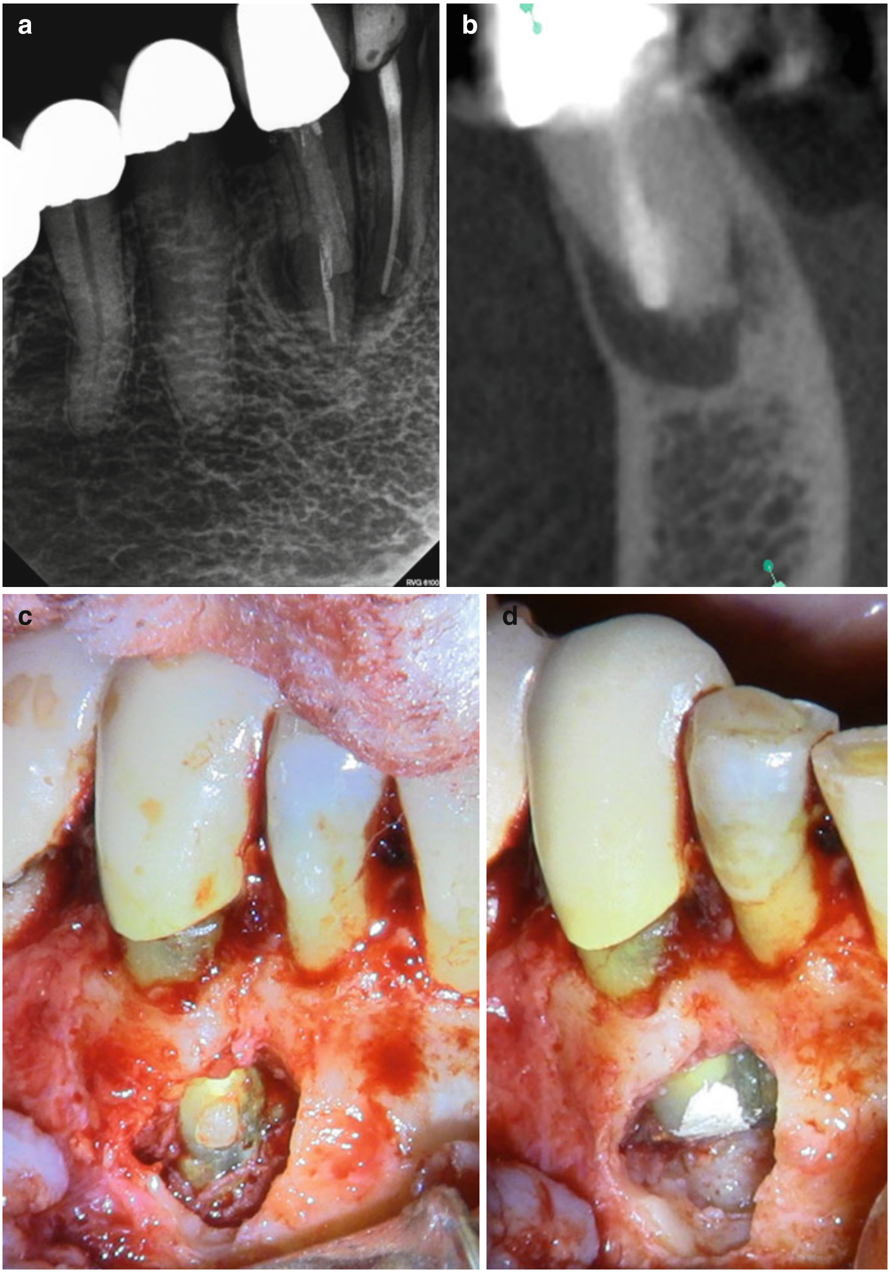

Fig. 1.5 (**a**) Digital radiographic image of tooth #27 showing fiber post placement mesial to canal space. (**b**) Cone beam CT image showing post perforating facial aspect of root. (**c**) Surgical clinical image showing fiber post perforating mesial-facial aspect of root. (**d**) Surgical clinical image showing root end resection and repair of perforation (Clinical photos attributed to Dr. Cynthia Tyler, University of Minnesota Division of Endodontics)

material has been advocated to help maintain repair materials inside the tooth and preserve the health and structure of the supporting bone and periodontal ligament. This technique, as described by Bargholz (2005), involves placing pieces of resorbable collagen membrane through the perforation and into the defect in bone. The collagen serves to recreate the outer surface of the root. MTA or another perforation repair material can then be layered against the collagen barrier without great risk of extruding the repair material beyond the root surface. After the perforation is repaired, the collagen membrane will be resorbed within a few weeks.

In the case of a large perforation, a perforation as a result of resorption, a perforation that does not heal after nonsurgical repair, or a perforation that is inaccessible from an orthograde approach, surgical repair of the root perforation may be an option (Tsesis and Fuss 2006). Generally this surgical repair consists of a reflecting the gingival tissue, accessing the area of the perforation via osteotomy if necessary, removing any inflammatory tissue around the site of perforation, and repairing the perforation with a perforation repair material, such as MTA, to create a permanent seal. It has also been suggested that guided tissue regeneration, by the use of a bone allograft and a membrane, may promote healing in surgical perforation repair sites where a significant amount of bone was lost due either to the inflammatory process or the osteotomy created to access the perforation area (Dean et al. 1997).

The risk of creating thin root dentin or root perforation is higher in certain teeth or roots where anatomic considerations, such as dentin thickness, canal shape and size, and external root shape are a factor (Sathorn et al. 2005). Mandibular incisors generally have a ribbon-shaped root, with more thickness of dentin in the buccal lingual dimension and very thin dentin in the mesial-distal dimension. With a round post space preparation, therefore, there is risk of thinning or even perforating the mesial or distal root dentin (Gluskin et al. 1995). Maxillary premolars with two roots also present an area of thin dentin on the furcal aspect of the buccal root (Lammertyn et al. 2009), making the palatal root the more ideal location for a post. Similarly, when a post is necessary in a maxillary molar, it is suggested that it be placed in the palatal root due to greater bulk of tooth structure in that root (Schwartz and Robbins 2004); however, the operator must also take into consideration the apical curvature of the palatal root (Bone and Moule 1986). Rigid post drills and posts will not follow root curvatures, so there is risk of perforating at the inner aspect of the curvature if the post drill used beyond the point of curvature. In the mandibular molar, the "danger zone" for perforation is on the distal aspect of the mesial root, just below the furcation (Berutti and Fedon 1992). Therefore, it is generally recommended to place posts in the distal root in these teeth (Schwartz and Robbins 2004). However, recent studies have shown that the furcal aspect of both the mesial and distal roots in the mandibular first molar can present areas of extremely thin dentin (Harris et al. 2013), so again it is advisable to remove as little tooth structure as possible when creating post space in this tooth, even in the distal root.

Additionally, post design can contribute to the risk for root fracture. Active threaded posts induce more stress into the dentin and carry with them a higher risk of root fracture (Felton et al. 1991). Threaded posts, therefore, should only be used in teeth with substantial remaining root thickness (Schwartz and Robbins 2004).

1.6 Coronal Microleakage

1.6.1 Orifice Barriers

Due to time constraints or patient scheduling conflicts, it may not always be possible to place a permanent coronal restoration immediately after root canal obturation. However, in order to provide an environment conducive to healing following root canal therapy, great care must be taken to ensure adequate sealing of coronal and apical structures. If the canal space is not sealed adequately, then microbial organisms, or their toxins, may induce an inflammatory response and lead to persistent disease. Obturated root canal systems may be recontaminated with microbes, or toxins, in various ways. A delay in placing a permanent coronal restoration following root canal treatment may allow coronal microleakage of the temporary filling material to occur. While oxide eugenol materials, such as Cavit (3M ESPE), have good sealing properties, there is a limit to the duration of their effectiveness. Fracturing of the coronal restoration, or tooth, resulting in exposure of the endodontic filling material and preparation of a post space in which the resulting dimension of apical filling material is less than adequate to maintain a seal are additional means of microleakage. The factor that the clinician has the most control over in regard to preventing recontamination of the root canal system is the use of a rubber dam during post space fabrication and coronal restoration. In a recent retrospective study by Goldfein et al. (2013), it was reported that when no rubber dam was used during post placement, 73.6 % of cases were considered successful at follow-up. 93.3 % of cases were considered successful when a rubber dam was used, and this difference was found to be statistically significant.

The impact of coronal microleakage as it relates to clinical outcome is not new. Allison et al. (1979) suggested the possibility that a poor coronal seal might contribute to clinical failure. In the following years, in vitro dye leakage studies by Swanson and Madison (1987) suggested that a significant amount of coronal microleakage is evident after only 3 days of exposure of gutta-percha to artificial saliva. The extent of microleakage in that study was similar at 3 days and 8 weeks, implying that coronal microleakage may be a rapid and significant event. Further studies have reinforced the significance of coronal microleakage. Torabinejad et al. (1990) found that 50 % of single-rooted teeth were contaminated with bacteria along the whole length of the root after 19 days or 42 days, depending on the contaminating microbial species introduced. In another study, Magura et al. (1991) assessed salivary penetration through obturated root canals and found that gutta-percha exposed coronally for up to 3 months should be retreated prior to placement of the definitive restoration. So, while the critical timeframe of coronal microleakage may be debated, the significant impact of adequate coronal seal in preventing microleakage is clearly evident.

As an ever-increasing range of restorative materials for post and core restorations are made available, it becomes a challenge to assess which materials will best protect the integrity of the sealed crown-root complex. Earlier studies by Bachicha et al. (1998) aimed to measure the microleakage of a stainless steel post system and a carbon-fiber post system luted with a range of cements, including zinc phosphate, glass ionomer, Panavia-21 (Kuraray Noritake), and C&B Metabond (Parkell Inc.). Statistical analysis of this fluid filtration study model showed that there was significantly more microleakage associated with the zinc phosphate cement than those cemented with dentin bonding cements. In a different study approach, Freeman et al. (1998) evaluated the number of mechanical load cycles required to cause preliminary failure of full cast crown restorations having standardized minimal ferrule height and three different post systems, including passive stainless steel ParaPost (Coltene) and dentin bonding composite core, threaded #2 Flexi-Post (Essential Dental Systems Inc.) and dentin bonding composite, and a custom cast post and core luted with zinc phosphate cement. Their findings suggest that in teeth restored with a post and core, the occurrence of preliminary failure is clinically undetectable, yet it allows leakage between the restoration and tooth that may extend down the prepared post space. None of the post and core systems used in their study surpassed the others in preventing or delaying preliminary failure. Increased ferrule length, however, greatly improved resistance to cyclic loading when an additional 10,000 cycles had been applied.

The use of intracoronal orifice barriers to prevent recontamination of the canal system is a restorative consideration with much support in the literature. Not only as an adjunctive measure against failure of a temporary restoration but also in consideration of canal morphology of multi-canal teeth. As Saunders and Saunders (1994) reminded us, it is very important to adequately seal the coronal part of the root canal system, due to the fact that molars have accessory canals that can be present in the floor of the pulp chamber. This could cause bacterial leakage into the furcation region. Excess sealer and gutta-percha should be removed to the level of the canal orifices and the pulp chamber sealed with a restorative material. In an in vitro bacterial leakage study by Chailertvanitkul et al. (1997), a 1 mm layer of Vitrabond (resin-modified glass ionomer liner, currently known as Vitrebond, 3M ESPE) placed over canal orifices of endodontically treated multi-rooted teeth that had been stored at 100 % humidity for 2 years was evaluated. Teeth that had been sealed with Vitrabond showed significantly less leakage of two types of bacteria apically through the gutta-percha obturant than those without a barrier after just 60 days. In another study by Maloney et al. (2005), the authors took into consideration the effect of thermocycling on a 1 or 2 mm glass ionomer intracoronal barrier in preventing coronal microleakage. A significant reduction in coronal microleakage was observed with the use of either a 1 or 2 mm intracoronal barrier.

1.7 Indications for the Use of Temporary Materials in Endodontics

1.7.1 Physical and Chemical Differences of the Temporary Restorations Used in Endodontics

The temporization of an endodontically treated tooth is a critical and fundamental step during the course of both treatment and restoration. The quintessential goal of temporization is to maintain a favorable environment for continued healing while allowing for efficient re-accessing of the chamber space. This is accomplished most commonly by using one or more temporary restorative materials in conjunction with a sterile cotton pellet or endodontic sponge barrier over the canal orifices. Three of the more commonly used temporary materials are IRM (Dentsply Caulk), Cavit (3M ESPE), and T.E.R.M (Dentsply Maillefer). The choice of materials and considerations of remaining tooth structure, as well as anticipated restorative time-frame, become essential decisions prior to temporization.

Intermediate restorative material (IRM) consists of a powder containing zinc oxide and polymethacrylate mixed with a eugenol liquid. The addition of polymethacrylate to the zinc oxide eugenol mixture provides the material with improved compressive strength, abrasion resistance, and hardness (Naoum and Chandler 2002). These attributes make IRM a strong enough material to restore marginal ridges and to withstand occlusal forces. However, the seal against coronal leakage provided by IRM is less effective than some of the other temporary materials available (Barkhorder and Stark 1990).

Cavit consists of zinc oxide, calcium sulfate, zinc sulfate, glycolacetate, polyvinyl acetate resins, polyvinyl chorine acetate, triethanolamine, and pigments. Cavit sets and expands upon contact with moisture providing an efficient fluid seal which may be easily removed for continued treatment. The required thickness of Cavit to provide an efficient fluid seal was evaluated by Pisano et al. (1998). In their bacterial leakage study, it was determined that a minimum thickness of 3.5 mm Cavit provided an adequate microbial barrier for 90 days in 85 % of the study samples. In comparison, the same thicknesses of IRM and Super EBA provided an adequate microbial barrier in only 65 % of the samples. One obvious limitation to Cavit is with its relatively poor wear characteristics and fracture resistance when needing to restore marginal ridges.

Taking advantage of both the effective sealing properties of Cavit and the superior wear characteristics of IRM, the use of a "sandwich" technique combining both materials has been advocated (Hagemeier et al. 1990). By this technique, 3.5 mm Cavit is placed above the cotton pellet to seal off the chamber from leakage, and IRM is then placed on top of the Cavit to provide the resistance fracture and wear (Fig. 1.6).

T.E.R.M., a temporary endodontic restorative material, is one of the newer options for temporization of the endodontic access. T.E.R.M. is a predosed visible light-cured resin containing urethane dimethacrylate polymers, inorganic radiopaque fillers, organic pre-polymerized filler, pigment, and initiators. As reported by Hansen and Montgomery (1993) in a 5-week thermocycling and leakage study, T.E.R.M. performed better than IRM. At 1, 2, and 3 mm thicknesses, T.E.R.M. maintained as tight a seal as at 4 mm, suggesting the usefulness when 4 mm is not obtainable when considering other materials such as Cavit or IRM.

While in vitro studies are often compelling, the inability to truly model conditions in vivo may call into question the appropriateness of their findings. A higher level of evidence is provided by clinical studies, such as with a study by Beach et al.

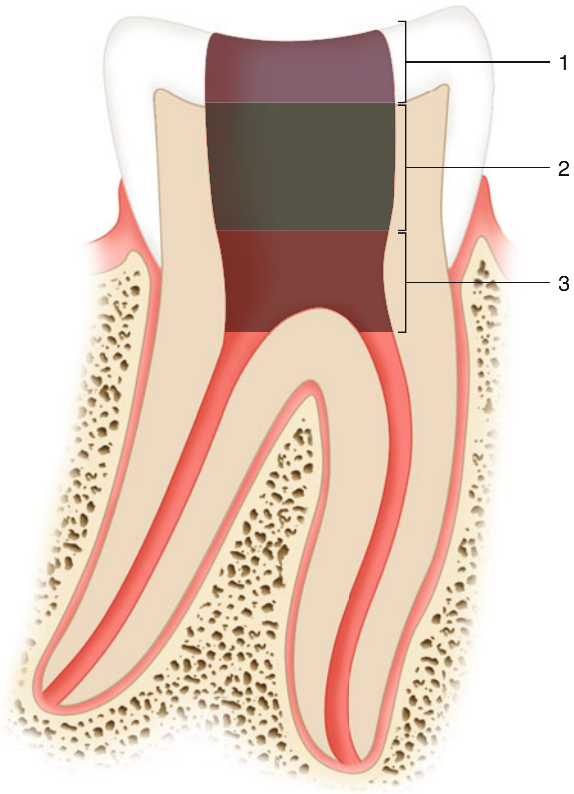

Fig. 1.6 Temporary restoration, "sandwich" technique. (*1*) IRM (Dentsply), (*2*) Cavit (3M ESPE), approximately 3.5 mm, (*3*) cotton spacer

(1996) comparing Cavit, IRM, and T.E.R.M. restorative materials for bacterial leakage in a human clinical study. The access openings of 51 endodontically treated teeth were randomly sealed with a 4 mm thickness of one of the three materials. Following 3 weeks from placement, microbial sampling was conducted both aerobically and anaerobically. Positive growth occurred in 4 of 14 T.E.R.M. samples and in 1 of 18 IRM samples. Cavit did not demonstrate leakage in any of the teeth sampled. In this study, Cavit provided a significantly better seal than T.E.R.M. over the study period.

Conclusion

The long-term prognosis for an endodontically treated tooth depends not only on the disinfection of the root canal space but continued protection of that space from bacterial contamination with a high-quality coronal restoration. Whether or not full coronal coverage or a post is indicated or if temporization is necessary prior to definitive restoration, it is important to consider techniques for protecting the root canal system from infection, all while preserving crown and root dentin, to insure the best enduring health and strength of the tooth.

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Effect of Endodontic Treatment Procedures on Canal Shape and Mechanical Properties of a Tooth

2

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Abstract

Endodontic treatment procedures induce changes in tooth structure and may shift stress distributions in treated roots that make them more prone to fracture. This chapter discusses mechanical properties and changes in dentin characteristics and shape of the root canal caused by root canal therapy. Moisture, irrigants, medicaments, obturation materials, temperature rise, and canal taper may induce these changes.

2.1 Mechanical and Structural Characteristics of Root Dentin

The tooth is the only mineralized organ that is located partially internal and partially external to the body (Giannini et al. 2004). To minimize fracture and wear during function, the tooth is composed of highly mineralized tissues with physical and mechanical properties determined by their composition and micromorphology (Gwinnett 1992). Crowns of teeth are covered by dental enamel, which is the

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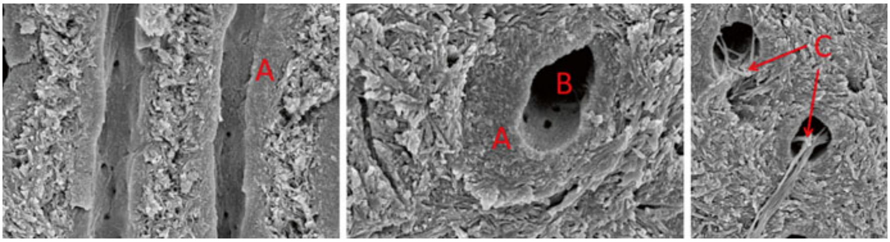

Fig. 2.1 Scanning electron microscope (SEM) micrographs of the dentin structure. *A* – Peritubular dentin. *B* – Dentinal tubules. *C* – Collagen fibrils

hardest tissue in the body containing 92–96 % inorganic material, 1–2 % organic material, and 3–4 % water by weight (Gwinnett 1992). Enamel is hard but brittle due to its high mineral content, with high elastic modulus and low tensile strength (Giannini et al. 2004). Studies have shown that mechanical properties of the enamel are dependent on the type and direction of the stress applied, as well as on the enamel prism orientation (Urabe et al. 2000; Giannini et al. 2004).

The dentin–enamel junction (DEJ), a biological interface between the enamel and dentin, may dissipate stress and inhibit further crack propagation (Lin and Douglas 1994). The DEJ has high fracture toughness and, along with the more resilient underlying dentin, supports the integrity of the enamel by preventing fracture during function (Craig and Peyton 1958). The dentin is the major structural component of the tooth. Prominent features in the microstructure of the dentin are tubules that radiate outward from the pulp to the DEJ in the coronal dentin and from the pulp in the root canal to the cementum in the root (Kinney et al. 2005). The dentin is a hydrated biological composite composed of 70 % inorganic material, 18 % organic matrix, and 12 % water by weight, with properties and structural components that vary with the location within the tooth (Mjör 1972). The collagen phase of the dentin contributes to a lower elastic modulus compared to that of the enamel (O'Brien 1987). The lower mineral content of the dentin is also associated with a lower hardness (O'Brien 1987). Dentinal tubules are surrounded by a highly mineralized cuff of peritubular dentin and an intertubular matrix mainly consisting of type I collagen fibrils reinforced with apatite (Fig. 2.1) (Tronstad 1973). The relative contribution of tubules, peritubular, and intertubular dentin varies significantly in composition with location (Marshall et al. 1997). These differences in composition are thought to have profound effects on the dentin's tensile strength (Carvalho et al. 2001).

The primary function of the human dentition is the preparation and processing of food through a biomechanical process of biting and chewing. This process is based on the transfer of masticatory forces mediated through the teeth (Versluis and Versluis-Tantbirojn 2011). Although the primary function of the dentin is mechanical, it has only been in the last few decades that its mechanical properties have begun to be understood in terms of its hierarchical microstructure (Kinney et al. 2003; Nalla et al. 2003). Understanding the mechanical behavior of the dentin and

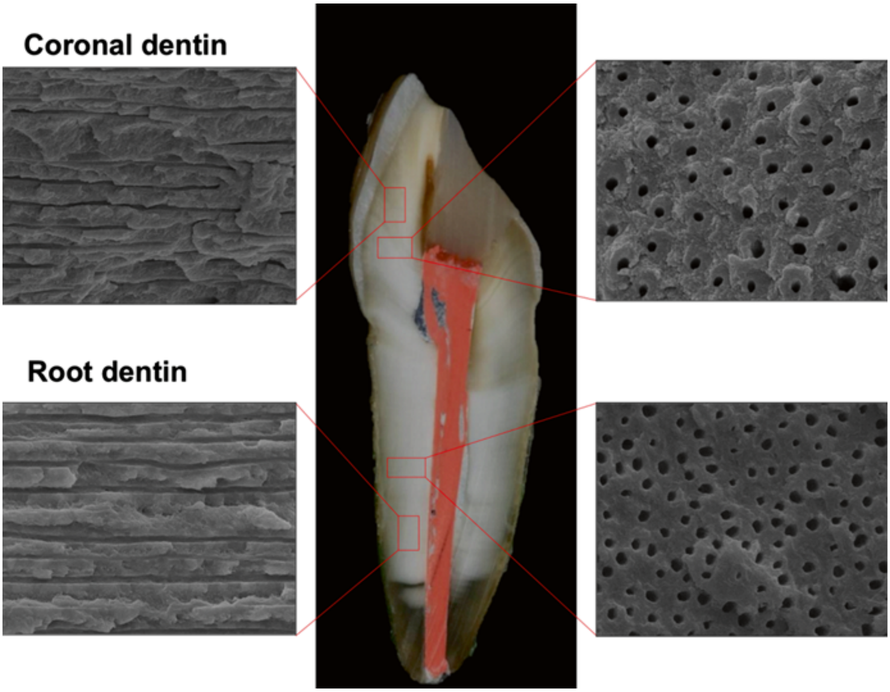

Fig. 2.2 Scanning electron microscope (SEM) micrographs of the structure of the coronal and root dentin perpendicular and parallel to dentin tubules

the detailed relations to the dentinal structure provides insight into the design strategies to recover tooth functions and helps to improve dental restoration techniques (Eltit et al. 2013).

The ultimate tensile strength of the dentin varies widely and is dependent on intra-tooth location and depth (Giannini et al. 2004). Soares et al. (2010) showed higher ultimate tensile strengths when a tensile force was directed perpendicular to tubule orientation. This may have been a result of the dentinal tubules being surrounded by mineralized collagen fibrils organized layer by layer on planes transverse to the tubules (Eltit et al. 2013).

The tooth is naturally organized to support and transfer stresses and strains generated by masticatory loads. The synergism of the enamel, coronal dentin, and root dentin creates an integrated organ that is capable of supporting high masticatory stresses (Fig. 2.2) (see mechanical properties of the enamel and dentin in Table 2.1). The root dentin is an important component in this structure to integrate the dentition with muscle–bone support. Human root dentin has higher flexural strength and more significant inelastic deformation than the coronal dentin (Eltit et al. 2013). When the tooth crown is structurally compromised by caries or defective restorations, a root canal treatment may be necessary to maintain tooth integrity and to provide stability for coronal rehabilitation.

Table 2.1 Mechanical properties of tooth structure (mean and standard deviation)

Tooth structure	Ultimate tensile strength – MPa[a] Parallel to prism/ tubule direction	Ultimate tensile strength – MPa[a] Perpendicular to prism/tubule direction	Compressive strength[b] – MPa	Elastic modulus – GPa
Enamel	40.1 (12.4)	17.6 (5.7)	261 (41.4)	87.5 (2.1)[c]
Coronal dentin	54.2 (19.5)	86.5 (20.2)	282.6 (34.5)	18.0 (1.5)[d]
Root dentin	49.8 (13.9)	64.7 (14.7)	233.5 (26.7)	21.5 (2.1)[d]

[a]Soares et al. (2010)
[b]Stanford et al. (1960)
[c]Habelitz et al. (2001)
[d]Brauer et al. (2011)

2.2 Factors That Predispose Endodontically Treated Teeth to Fracture

The causes of tooth fracture have been associated with occurrence of sudden impact trauma resulting from falls, fights, motor vehicle accidents, epileptic fits, and laryngoscope misuse, and with fatigue failure of tooth structure resulting from repeated stress overloading (Tang et al. 2010). When loads are applied to a structure it deforms (strain) and stresses are generated. This is how a tooth performs its structural function. But if such stresses become excessive and exceed the strength of the tooth, structural failure may occur (Soares et al. 2008).

Endodontic treatment is a common clinical procedure, usually provided with the objective of retaining teeth in which the pulp has become irreversibly infected or necrotic (Driscoll et al. 2002). Endodontic procedures include the removal of pulp tissue and the heavily infected dentin surrounding the pulp. These procedures involve mechanical and chemical events that may interfere with the natural stress–strain distribution in the tooth structure, increasing the risk of failure.

The fracture of endodontically treated teeth is a common clinical failure, which could require extraction. A factor that may predispose such teeth to fracture has been identified as changes in the mechanical properties of the dentin (Fig. 2.3). Dentinal collagen makes a considerable contribution to the mechanical properties of the dentin (Grigoratos et al. 2001). Changes in these collagen fibril cross-links may contribute to the so-called brittleness of the pulpless teeth (Soares et al. 2007). More immature and fewer mature cross-links in endodontically treated teeth might account for a decrease in tensile strength (Gutmann 1992). Loss of pulp vitality also influences moisture content of the dentin. Additionally, iatrogenic factors associated with various operative procedures may contribute to the fracture of the endodontically treated teeth, although most of these risks are controllable (Tang et al. 2010).

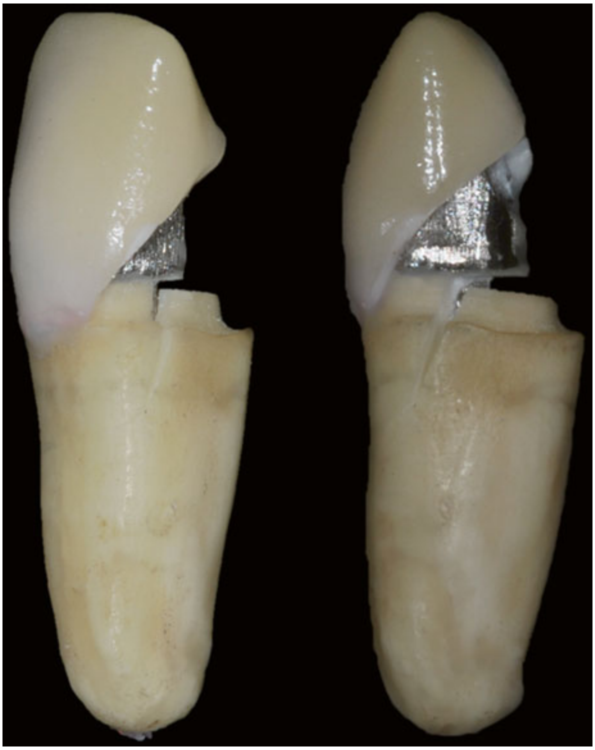

Fig. 2.3 Fracture of an endodontically treated tooth demonstrating fragility of the root dentin

2.2.1 Immature Teeth with Incomplete Root Formation

Immature teeth with diseased or necrotic pulps generally exhibit arrested root development and open apices. After endodontic treatment, immature teeth are severely weakened because of wide, flared canal spaces and thin dentin walls (Brito-Junior et al. 2014). Apexification and root rehabilitation with a relined glass fiber post (see Chap. 5 (Fig. 5.4)) might restore the reduced mechanical integrity resulting from incomplete root formation (Tang et al. 2010; Brito-Junior et al. 2014). Furthermore, finite element analysis demonstrated that endodontically treated teeth without fiber post had higher stress concentrations in the root dentin than those restored with resin composite or other restorative techniques that used fiber posts (Fig. 2.4). The restorations with posts exhibited higher fracture resistance (Brito-Junior et al. 2014).

2.2.2 Endodontic Access Preparation

The actual effect of the endodontic access preparation is controversial. Some studies have shown that the loss of tooth structure from endodontic access preparation might increase the occurrence of fractures (Zhi-Yue and Yu-Xing 2003). Other

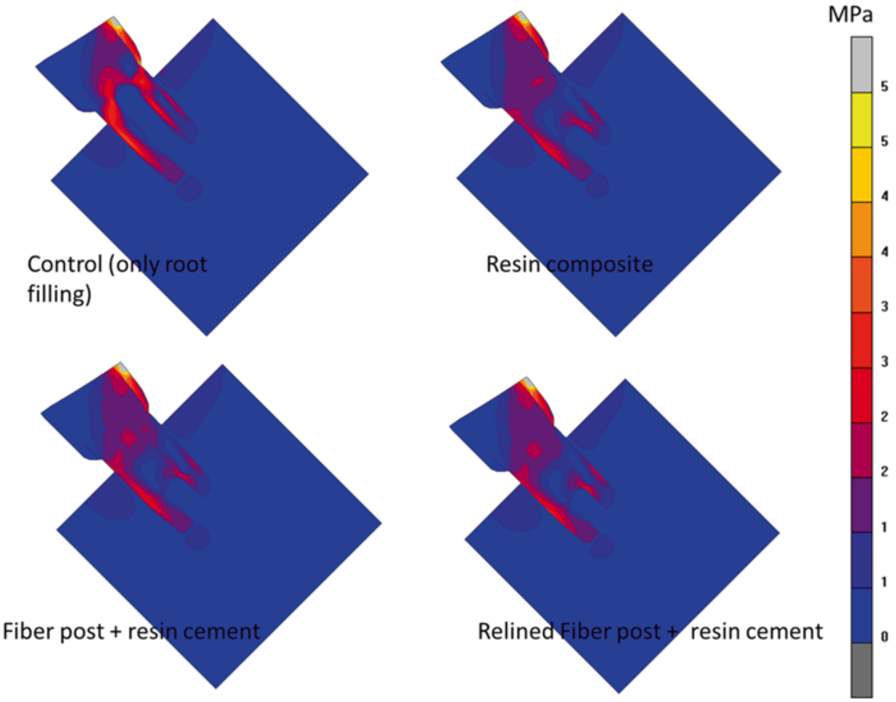

Fig. 2.4 Von Mises stress distributions in the tooth with incomplete root formation restored with different restorative options (Figure adapted from Brito-Junior et al. (2014)). Von Mises stress is an equivalent stress that shows the general stress state of all stress components

authors showed that a conservative root canal access resulted in less tooth deformation (Tang et al. 2010).

> There is a consensus that tooth deformation increases progressively after root canal preparation and obturation, in particular after post space preparations (Tang et al. 2010).

2.2.3 Root Canal Preparation: Stress Distribution Generated in Root Dentin During Root Canal Shaping and Effect on Vertical Root Fracture

Endodontic treatment is a predictable therapy with a success rate up to 97 % (Salehrabi and Rotstein 2004). However, many completed cases may still be lost over the patient's lifetime. The most common reasons for catastrophic failure of endodontically treated teeth [vertical root fracture (VRF)] are weakening of the residual tooth structure by caries and overpreparation and the post system used during the rehabilitation (Fuss et al. 2001; Tsesis et al. 2010). VRF is one of the most disappointing complications of root canal treatment, which may result in a tooth extraction (Tamse 2006). VRF of endodontically treated teeth is a clinical problem of increasing significance.

VRF is usually diagnosed a few years after the endodontic and restorative treatments are completed (Vire 1991; Fuss et al. 2001). Root canal preparation procedures have been reported to increase the risk of root fracture and crack formation by reducing root dentin integrity or creating defects inside root canals that may act as stress concentration or crack initiation sites (Schafer and Lau 1999; Schafer et al. 2004; Adorno et al. 2009; Kim et al. 2010).

Many nickel–titanium (NiTi) rotary instruments have been developed and introduced in the last decades. These instruments have brought convenience and efficiency to root canal shaping, which reduces procedural errors (Schafer and Lau 1999; Schafer et al. 2004). Most clinicians prefer these systems because of their advantages, such as improved cutting efficiency and time saving (Schafer and Lau 1999; Schafer et al. 2004). Nevertheless, some functions of NiTi rotary systems such as their cleaning ability, increased stresses accumulated in the root dentin, and the inability to adequately prepare oval canals, are still controversial. File design is likely to affect the shaping forces on the dentin during instrumentation (Lam et al. 2005; Kim et al. 2008). During instrumentation a root canal is cut and enlarged by the contact between instruments and dentin walls. The numerous momentary contacts between instrument and canal wall create stress concentrations in the dentin and may induce dentinal defects and microcracks or craze lines (Blum et al. 1999; Kim et al. 2008, 2010). Adorno et al. (2009) reported that root canal preparation alone significantly weakened roots, especially when the working length is longer than optimal, and may create apical root cracks. Bier et al. (2009) showed dentinal damage, such as craze lines and partial cracks, in teeth that were prepared with several brands of NiTi rotary instruments, whereas no defect was observed with hand files (Bier et al. 2009). This type of defects are associated with increased susceptibility to VRF because functional loads or stresses from the repeated occlusal forces after restoration can be amplified at the tip of those defects and initiate or propagate into VRF (Tamse et al. 1999; Kim et al. 2010).

Stresses in the root dentin during instrumentation by various NiTi instruments have been studied using finite element analysis (FEA). Kim et al. (2010) investigated the potential relationship between NiTi instrument design and the incidence of VRF and crack formation. This study compared stresses generated in the apical root dentin during rotary instrumentation in a curved canal with NiTi files featuring different cross sections and shaft geometries. It was shown that during root canal instrumentation, under certain clinical conditions (e.g., in a severely curved canal), file design (with a big taper and/or stiff characteristics) might generate stresses that exceed the tensile strength of the dentin (Fig. 2.5).

On the other hand, some NiTi instrument systems for coronal canal flaring, which are used in early root canal preparations, were reported to have lower rates of crack formation than those found with Gates-Glidden drills (Arslan et al. 2014).

Recently introduced reciprocating NiTi instrument systems use a back-and-forth rotational movement instead of continuous rotation (Yared 2008). Many articles

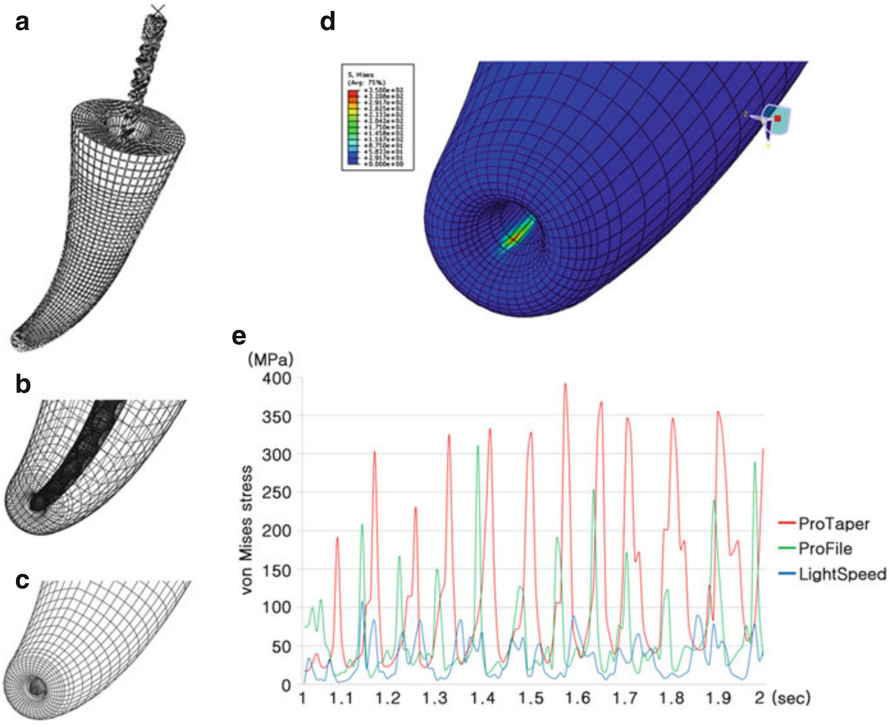

Fig. 2.5 Finite element analysis evaluating stress concentrations during instrumentation. (**a**–**c**) Finite element models of the root canal and instrumentation. (**d**) Representative figure of von Mises stress concentration at the apical dentin during simulated shaping rotation. (**e**) Graph showing cyclic stress profile during simulated shaping in a node of the model where the highest von Mises stress was generated (Kim et al. 2010)

have since been published about reciprocating NiTi instruments, which are used in a single file technique for clinical convenience and efficiency (Kim et al. 2012; Shin et al. 2014). The conclusions regarding apical crack formation in many of these articles are contradictory (Bürklein et al. 2013; Abou El Nasr and Abd El Kader 2014; De-Deus et al. 2014). Although root canal preparation with either rotary or reciprocating instruments resulted in dentinal defects, reciprocating files resulted in significantly more incomplete dentinal cracks than full-sequence rotary systems at the apical level of the canals (Bürklein et al. 2013). On the other hand, ProTaper rotary files (Dentsply Maillefer) were reported to have significantly more micro-cracks than ProTaper hand files and WaveOne Primary reciprocating files (Dentsply Maillefer). NiTi hand K-files did not produce microcracks at any level inside the root canals (Ashwinkumar et al. 2014). In one article, with regard to the potential risk of root cracks from the file system, WaveOne instruments induced the least amount of cracks and exhibited the greatest resistance to fracture compared with ProTaper F2 files whether used in reciprocating or rotating motions. It was suggested that the alloy from which the instrument was manufactured was a more important factor for the dentin damaging potential than the motion of instrumentation (Ashwinkumar et al. 2014). Other authors found no causal relationship between dentinal microcrack formation and root canal preparation procedures with the reciprocating systems (De-Deus et al. 2014).

In another recent development, the design of a self-adjusting file (SAF) – an instrument without an internal core and with a mesh-like structure – may produce minimal stress concentrations in the apical root dentin during shaping of the curved root canal, which may increase the chance of preservation of root dentin integrity with a reduced risk of dentinal defects and apical root cracking (Yoldas et al. 2012; Kim et al. 2013; Liu et al. 2013).

Comparing primary root canal treatment with retreatment, retreatment procedures may result in more defects than initial treatments (Shemesh et al. 2011). Therefore, it was suggested that when assessing the outcomes of endodontic retreatment, substantial damage to the root canal walls should be considered. Practitioners that are aware of controllable and uncontrollable risks during dental treatments may be able to reduce potential tooth fractures (Tang et al. 2010).

> Although the precise effect of each shaping procedure is still debatable, it is well accepted that stress levels during shaping and the susceptibility to apical root cracking after shaping vary with instrument design.

2.2.4 Loss of Dentin During Endodontic Treatment

The removal of the inner dentin negatively influences the stress distribution (Santos-Filho et al. 2014). In some situations, root canals become flared because of the progression of caries associated with endodontic access and overpreparation. The resulting flared root canals have thin root dentin walls, which may be too weak to resist physiologic occlusal loading, thus becoming more susceptible to fatigue and fracture (Coelho et al. 2009; Silva et al. 2011). This fact makes the restorative procedure of these teeth more difficult. Therefore, the rehabilitation of weakened root-filled teeth has been recognized as a challenge. In Chap. 5 (Section 5.4) we will explore in detail a method that uses relined glass fiber posts to create a homogeneous stress distribution to the external dentin surface that is similar to a sound tooth (Santos-Filho et al. 2014; Coelho et al. 2009).

2.3 Modifications Caused by Irrigants, Medicaments, and Root Canal Filling Materials on Mechanical Properties of the Root Dentin

The success of root canal treatment depends on the root canal system being thoroughly cleansed and disinfected. To complement proper cleaning and shaping of the root canal system, filling with a biologically inert and dimensionally stable material is a major objective of root canal treatment (Heulsmann et al. 2005). Substances used during chemical–mechanical preparation may alter the collagen structure, which contributes considerably to the mechanical properties of the dentin (Renovato et al. 2013). Sodium hypochlorite (NaOCl) and ethylenediaminetetraacetic acid (EDTA) are common solutions used as endodontic irrigants. Saleh and Ettman (1999) evaluated the effect of several endodontic irrigation solutions on the microhardness of the root canal dentin. The canal portions in the root segments were irrigated with 3 % H_2O_2, 5 % NaOCl, and 17 % EDTA. The results showed that irrigation with either H_2O_2/NaOCl or EDTA decreased the microhardness of the root dentin. Irrigation with EDTA lowered dentin hardness compared to H_2O_2/NaOCl irrigation. These irrigants also changed the mechanical properties of the dentin, such as flexural strength and elastic modulus. Grigoratos et al. (2001) evaluated the effect of NaOCl (3 and 5 %) and saturated calcium hydroxide ($Ca(OH)_2$) solutions on the flexural strength and elastic modulus of the dentin using a three-point bending test. The results showed that NaOCl reduced both elastic modulus and flexural strength, while the saturated $Ca(OH)_2$ reduced the flexural strength but not the elastic modulus of the dentin. Prolonged use of high concentration of EDTA and NaOCl solutions may thus increase the risk for root fracture. Clinicians should be aware that the irrigants should be completely removed from the canal prior to the root-filling procedure.

Gutta-percha is still the most widely used material for root canal filling in endodontic treatment. Materials used during the root-filling therapy must be radiopaque and easily handled, have antimicrobial properties, and provide a stable adhesive seal and reinforcement of the root canal dentin walls (Tang et al. 2010). Although gutta-percha may provide some support, reinforcement of the canal walls requires adhesion of the endodontic material to root canal walls, which has been shown to improve the fracture resistance of endodontically treated teeth (Tang et al. 2010). In the case of endodontic retreated teeth, additional procedures are involved with the removal of filling material and contaminants that can negatively influence the mechanical properties of the root dentin (Guedes et al. 2014). Signs of endodontic treatment failure, including the presence of apical periodontitis and posttreatment symptoms, are important indicators that further intervention is required (Estrela et al. 2009). During root canal retreatment, the radicular and coronal dentin is exposed to gutta-percha solvents. These solvents may modify the chemical composition of the dentin surface and affect its interaction with the restorative and root-filling materials. The use of xylene and orange oil as gutta-percha solvents during root canal retreatment had no significant differences in the bond strength of the fiberglass posts cemented to the radicular dentin. The use of eucalyptol significantly decreased the bond strength of fiberglass posts in the cervical and middle third of the roots, with higher bond strength values in the cervical third than the apical third (Guedes et al. 2014).

2.4 Structural Moisture Content of Endodontic Treated Teeth

In the confined environment of a vital pulp and adjacent dentinal tubules, the presence of free water results in increased dentin viscoelasticity and also facilitates the absorption and distribution of energy before tooth fracture occurs (Tang et al. 2010). On the other hand, the dehydration of the dentin tends to increase its elastic modulus, proportional limit, and especially ultimate strength, by increasing the stiffness and decreasing the plasticity beyond the proportional limit (Tidmarsh 1976). The reduction in tooth structure and the effect of dehydration on the dentinal tubules are widely considered to be the main reasons for increased brittleness associated with endodontic treated teeth (Tidmarsh 1976). The moisture content of the coronal dentin is approximately 13.2 %, but the coronal dentin has twice the number of tubules than radicular dentin per unit area (Gutmann 1992). Presumably, with fewer tubules, the radicular dentin would have lower moisture content. During aging, greater amounts of the peritubular dentin are deposited, decreasing the amount of organic materials that may contain moisture. Physiological transparent dentin is first formed in the apical dentin adjacent to the cementum and extends coronally and toward the root canal with increasing age (Vasiliadis et al. 1983). The physiological transparent root dentin, as distinguished from pathological transparency subjacent to caries, appears to form without trauma or caries lesion as a natural part of aging (Vasiliadis et al. 1983). In addition, the mineral concentration is significantly higher in the transparent dentin and its fracture toughness decreases by 20 % (Kinney et al. 2005; Perdigao 2010; Tang et al. 2010). Endodontic treated teeth have less moisture than vital teeth. The calcified tissues of pulpless teeth had 9 % less moisture than the vital teeth (Helfer et al. 1972; Lee et al. 2004). This reduction in water content after endodontic treatment could result in dentin tissue shrinkage, inducing stresses leading to crack formation, and these cracks could initiate tooth fracture. This may explain a significant decrease in ultimate strength values observed in the endodontic treated teeth (Soares et al. 2007). Reduced shear strength and toughness have also been reported with a simultaneous reduction in tooth stiffness (Carter et al. 1983; Reeh et al. 1989).

2.5 Effect of Different Canal Tapers on Radicular Stress Distributions

Stress in endodontically treated teeth is directly associated with fracture resistance because root fracture occurs when stress exceeds the mechanical strength of the radicular dentin (Lertchirakarn et al. 2003). Regardless of dentin strength, the amount of stress is always determined by three factors: deformation properties (such as elastic modulus), geometry (shape of root and canal), and boundary conditions (root loading and support). Stress is, therefore, affected not only by changes in dentin properties from the endodontic treatment but also by changes in root canal

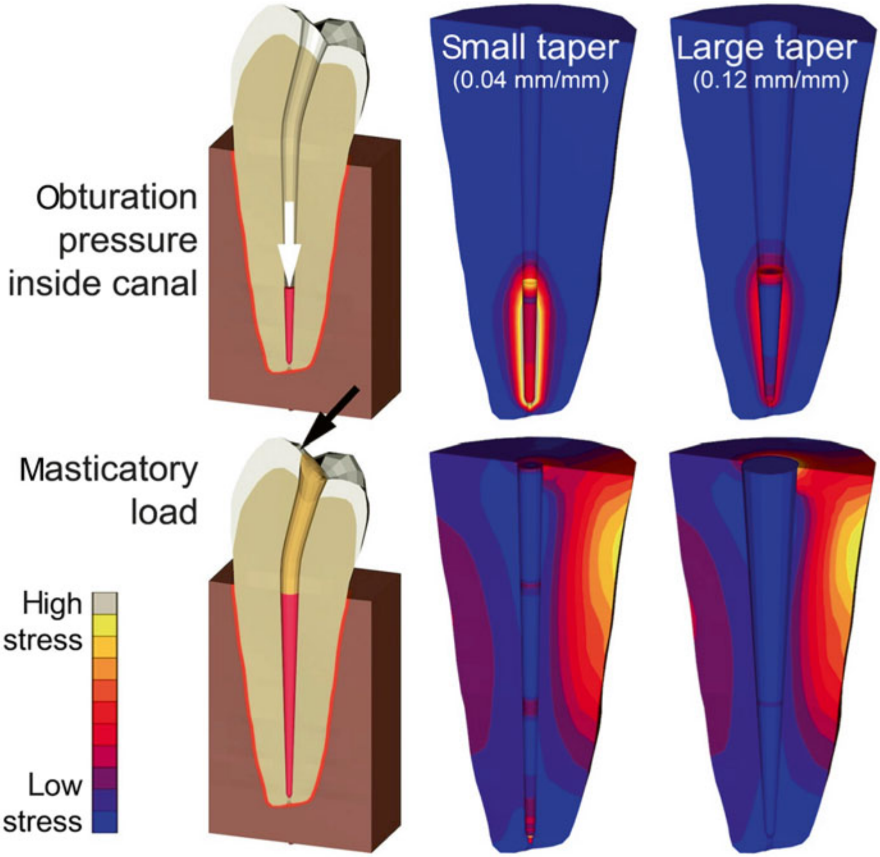

Fig. 2.6 Radicular stress distribution (modified von Mises stress) depends on type of loading: during endodontic procedure, the highest stresses are at the canal wall; during functioning, under masticatory loading, stresses are at the external root surface. For large tapers, radicular stresses are generally lower than small tapers during obturation, but higher during masticatory loading (Figure adapted from Rundquist and Versluis (2006))

shape and forces exerted during endodontic treatment. This dependency on multiple factors supports the lack of unambiguous correlations between endodontic treatment and fracture of the root canal treated teeth (Pitts et al. 1983). Roots are subjected to two types of loads: (1) pressure from inside on the canal wall during treatment and (2) loading during masticatory function. The effect of canal taper on radicular stress distribution is different for each type of these loading conditions.

When forces are applied on the canal wall during obturation, radicular stresses are the highest at the canal wall, whereas stresses at the external root surface are relatively minor (Fig. 2.6) (Sathorn et al. 2005; Rundquist and Versluis 2006). Large tapers increase the canal wall surface area compared to small tapers. For the same compaction or spreader loading, large tapers will therefore distribute the forces over a larger area and consequently have lower radicular stresses during obturation than canals with small tapers (Harvey et al. 1981; Holcomb et al. 1987; Rundquist and Versluis 2006). However, when a canal is widened further, the thickness of the root wall decreases, which leads to reduced wall stiffness and thus increased stress levels (Holcomb et al. 1987). When compaction or spreader forces are applied inside the canal in a circular root cross section, the optimal ratio between canal and root radius for the stress at the canal wall was between 0.3 and 0.6 (Rundquist and Versluis 2006). Note that stresses at the external root surface increase with increasing canal radius (Wilcox et al. 1997), although they remain lower than at the canal wall. For noncircular roots, pressure applied internally at the canal wall will cause higher stress throughout the flattened thinner root dentin walls, although they also remain the highest at the canal wall (Versluis et al. 2006).

During function, the most significant loading on the root is bending due to the lateral component of masticatory forces. This completely changes the stress distribution in a tooth compared to the distribution during endodontic treatment. The highest radicular stress during functional tooth loading occurs at the external root surface at the cervical third (Fig. 2.6) (Rundquist and Versluis 2006; Chatvanitkul and Lertchirakarn 2010; Chen et al. 2012). Roots imparted with larger canal tapers will have higher stresses than those with smaller tapers, mainly due to reduced root stiffness from the loss of structural tissue mass from the larger access opening and enlarged canal. However, the difference between small and large tapers is relatively small. The explanation is that during tooth bending the center of a root is not stressed. Therefore, removing the unstressed dentin in a root canal treatment hardly affects the root stresses.

Based on general stress considerations, it can be concluded that removing substantial amounts of the dentin using large tapers will generally weaken an endodontically treated tooth, although the effect on root fracture is likely modest. Root fracture of endodontically treated teeth is more likely affected by local stress raisers, some of which may have been introduced during root canal preparation or obturation (Shemesh et al. 2011; Barreto et al. 2012). Radicular stress distribution during the endodontic treatment suggests that this is likely the most critical phase, especially for canals with small tapers. Small tapered canals overstress the radicular dentin more easily and thus initiate or propagate cracks, particularly in the apical third. Larger tapers are less likely to overstress the radicular dentin and are more likely to smooth the canal walls, which also reduce stresses (Sathorn et al. 2005). However, even with large tapers, not all walls can be smoothed entirely (Peters 2004). Fortunately, it has been shown that creating fully round preparations reduces stress concentrations, even when fins are not completely smoothed (Versluis et al. 2006). Finally, larger tapers offer more surface area to bond posts, although interfacial stresses are likely to increase with increasing post diameter.

2.6 Root Dentin Strain and Temperature Rise During Endodontic Treatment and Post Space Preparation

As seen in the preceding section, fractures are likely to start at the canal wall and propagate toward the root surface. Procedures performed during root canal treatment may cause crack initiation, and fatigue processes may further propagate these cracks. For teeth with minimal coronal structure, a post is indicated to retain and improve the distribution of the functional load. The additional steps to be performed in the root (removal of obturation materials, post space preparation, and post cementation) may result in thermomechanical alterations to endodontically treated teeth (Ratih et al. 2007; Amade et al. 2013). These procedures may damage the tooth structure and the surrounding supportive structure. Tooth ankylosis or bone necrosis and resorption are also possible outcomes (Eriksson and Albrektsson 1983). Additionally, strain is generated in the root dentin at the same time as the heat production and may be a main or contributing factor in vertical root fracture (Amade et al. 2013).

High temperature levels may damage the bone and periodontal ligament. Bone tissue is sensitive to temperatures above 47 °C (Eriksson and Albrektsson 1983). Exposing the periodontal ligament to a 43 °C temperature may result in protein denaturation (Sauk et al. 1988). However, it is generally agreed that 10 °C is the critical temperature increase at which damage can occur in the supporting tissues (Saunders and Saunders 1989).

Amade et al. (2013) measured real-time strain and temperature rise on the root dentin external surface from the beginning of endodontic treatment to the end of the post space cementation (Fig. 2.7). A substantial condensation force is necessary to achieve deep initial insertion of the spreader for canal filling (Schmidt et al. 2000). This finding may explain the higher strain levels recorded in the cervical region than in the apical region. The use of a larger instrument and the movements performed by the operator during the gutta-percha condensation resulted in more contact (for a longer time) on the cervical root canal walls. Removal of obturation materials and post space preparation were considered the most critical heat generating procedures in endodontics. The removal of obturation materials showed a significantly higher temperature rise at the cervical root surface, but the range observed in this procedure (3.0–7.8 °C) was lower than the 10 °C considered the critical temperature for tissue damage. An increase in temperature of 10.8–14.0 °C was measured during the post space preparation for a fiberglass post, which exceeded the critical temperature for tissue damage. Some factors may influence the heat generation during post space preparation, such as reamer type, operator force, friction between the reamer and canal walls, and the condition of the drills (old or new) during post space preparation (Saunders and Saunders 1989). Irrigation may reduce temperature rise during the post space preparation. Clinicians must be careful during the post space preparation by using new drills that cut the dentin with less friction and lower heat generation. In order to prevent temperature rise, the post space preparation should be performed intermittently with continuous irrigation.

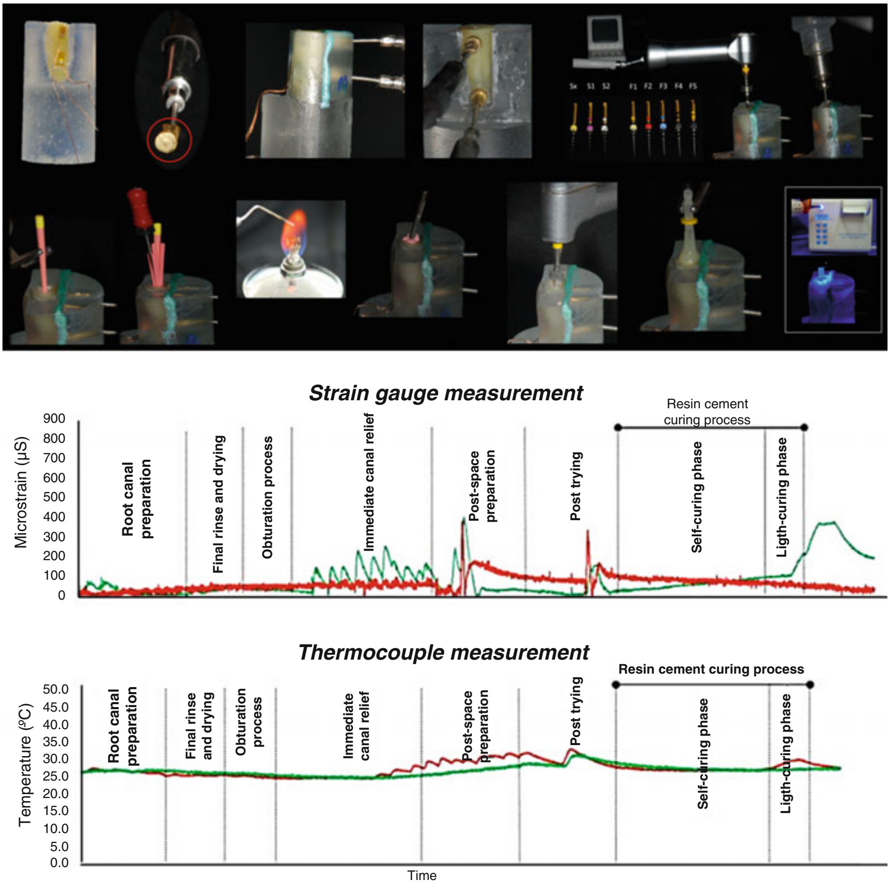

Fig. 2.7 Dentin root strain and temperature rise measured during endodontic treatment and cementation of glass fiber post (*Red line*: Cervical third and *Green Line*: Apical third) (Figure adapted from Amade et al. (2013))

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Restoring the Endodontically Treated Tooth: Treatment Planning Considerations

3

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Abstract

The objective of this chapter is to provide different treatment considerations to guide the clinician in the practice of evidence-based dentistry when performing treatment plans for endodontically treated teeth. As some of the existing literature is not clinically relevant, one must understand the limitations of published studies as they apply to clinical dentistry.

There are known clinical complications one could anticipate when attempting to restore a severely weakened vital or non-vital tooth with minimal residual sound tooth structure, incomplete ferrule, and fewer than two proximal contacts. The decision to endodontically treat a tooth should be based on its expected function within the entire dentition and whether or not it could predictably utilize its function for a long time. When the integrity of the enamel and dentin is compromised, one should consider coronal coverage, whether the tooth is vital or non-vital. Other chapters will discuss the different post and core materials and alternatives.

Ultimately, it is our responsibility to inform the patient of the risks/benefits and effort involved in attempting to maintain and restore a tooth.

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3.1 Introduction

The oral cavity… one of the most hostile environments there is. Yet, teeth have found shelter in it. The human tooth presents in various forms and shapes with a unique history of restorations and/or trauma. Stem cell-based biological tooth repair and regeneration is not part of the restorative dentist's armamentarium just yet. However, as clinicians, we are often confronted with situations where we feel that we have to take upon the role of the "herodontist." It is not uncommon for a patient to present with a dentition ornamented with different types of restoration materials: gold foil, silicate, amalgam, composite resin, and ceramics, just to name a few. Sometimes, a medley of these materials is present on the same tooth. Whether upon a routine examination or when evaluating an emergency patient with a trauma or a with a periapical lesion, practitioners must agree, in syntony with the patient, on the fate of problematic teeth. Before deciding on the outcome of a tooth with a periapical lesion or one that is extensively restored or severely damaged due to a carious lesions or trauma, the clinician must first assess the clinical status of the dentition as a whole, then that of the tooth, and have a clear understanding of the patient's signs, symptoms, and chief complaint. Guided by the patient's needs and preferences, and combining his or her experience with scientific evidence, the clinician must then practice the art of evidence-based dentistry. A methodological approach to every clinical situation can facilitate the thought process that takes place during treatment planning of the tooth, whether it is endodontically treated or not.

This chapter will discuss the treatment planning considerations that the clinician must walk through as he or she is faced with a moderate to severely damaged tooth with or without lesion of endodontic origin. After the establishment of a pulpal diagnosis, the evaluation of the remaining sound tooth structure and its relation to the periodontium, a decision is made on the restorability of the tooth. If it is restorable and the patient wishes to keep the tooth, one must consider the function the tooth will serve within the entire dentition and the stress it will be subjected to. In order to achieve full function and a predictable outcome, will the tooth require root canal therapy or a retreatment? Will the tooth necessitate a full coverage restoration with or without a post and core? Is there a ferrule effect or does the tooth need crown lengthening and/or orthodontic extrusion? This chapter will also be discussing the impact and outcome of such modalities. Finally, we will review different options if it is the patient's final decision to extract the tooth.

3.2 Diagnosis

3.2.1 Assessing the Pulpal Status

An accurate diagnosis must be made to provide the appropriate treatment. After collecting the necessary information on the patient's background through a meticulous medical and dental history, the clinician must pay careful attention to the signs and symptoms that are present in order to determine pulpal status. Even with an array of clinical tests, it is difficult to make a precise diagnosis as the pulp gradually evolves from one pulpal status to another. It is beyond the scope of this chapter to go in detail about endodontic diagnosis. Practically, we can say that root canal therapy is indicated when the pulpal status is irreversible pulpitis or pulpal necrosis. Nevertheless, when there is not enough sound tooth structure to serve as a foundation for a planned prosthetic procedure, it is sometimes indicated to perform an elective root canal treatment in situations of reversible pulpitis with deep carious lesion or normal pulp (Carrotte 2004).

3.2.2 Endo/Perio Lesions

Oftentimes, there is a close connection between the periodontal tissues and the pulpal tissues, whether through the apical opening or through lateral canals. Pulpal disease could cause periradicular lesions that take the same appearance as lesions of periodontal disease, at least radiographically. Accurate analysis of the combined information regarding the status of the pulp, the periradicular lesion, and the presence/absence of infraction or vertical root fractures will help the clinician to obtain the proper diagnosis and determine whether the problem is of an endodontic origin, a periodontal origin, or a real combination of both.

The pulp can be tested to determine its status. However, even necrotic pulps may have pain receptors that can be stimulated and lead to a false-positive response (Dummer et al. 1980). Sometimes, when using vitality tests, the presence of adjacent metal-based restorations might lead to a false diagnosis (Stock 1995). In most cases, if the testing indicates a pulp disease, a conventional root canal treatment can help in the healing of the periradicular lesions. It is uncommon for periodontal disease to be limited to a single tooth, and, generally, pockets are wider when of periodontal origin.

Other origins for periradicular lesions are developmental malformations, failing root canal treatments, and poor coronal restorations that provide a pathway for bacterial contamination (Ray and Trope 1985; Saunders and Saunders 1990, 1994). Root perforations as a result of extensive caries lesions, or resorption, or iatrogenic reasons during instrumentation of canal can also be responsible for a combined endodontic-periodontal problem (Seltzer et al. 1970).

3.2.3 Resorption

The dental pulp is an integral part of the rest of the body, and when there is disruption/rupture of the neurovascular supply in an otherwise normal pulp, ingress of bacteria could occur and pulpal necrosis could result (Andreasen and Kahler 2015), that is, of course, besides the potential injury to the periodontium and surrounding bone. Compromise of the neurovascular supply and trauma to the periodontal ligament may lead to resorptive processes that could sometimes be stopped provided the appropriate treatment is performed (Fig. 3.1). By completing a root canal therapy

Fig. 3.1 (**a**) A patient presented to the clinic complaining of an unusual "bump on her gum". Intraoral examination revealed localized swelling on the labial mucosa, buccal of left maxillary central incisor. Probing around the tooth was within normal limits and the patient was asymptomatic. Percussion was inconclusive on all anterior teeth. The patient could recall a history of dental trauma a year prior to the examination. This periapical radiograph of the left maxillary central incisor shows a periapical radiolucency with what seems to be a communicating internal-external inflammatory resorption. The tooth tested non-vital to pulpal testing. (**b**) Endodontic treatment was initiated and an attempt to induce calcification by using calcium hydroxide alone was made. (**c**) Root canal therapy was completed and adjunct surgical procedure was performed to apply ProRoot MTA (Dentsply Tulsa Dental Specialties) on the buccal aspect of the root, where the resorption communicated with the periodontal ligament space. A fiber post was bonded into the root canal and a provisional crown was fabricated

(Heithersay 1999) or performing a decoronation (Malmgren et al. 2006), the clinician could salvage a tooth prior to the resorption process breaking down a significant amount of tooth structure. The clinician must keep in mind that resorption could be trauma induced or idiopathic (Rivera and Walton 1994) and could also be in conjunction with a root fracture. It is important to assess the type of resorption as some do require root canal treatment and some do not. An evaluation by the endodontist might be of order.

3.2.4 Periodontal Considerations

There are many factors to be evaluated when assessing the periodontal condition. The age of the patient, the initial bone loss, the probing depths, the clinical attachment loss, the mobility, the root form, the furcation involvement, and whether or not the patient is a smoker are to be considered when determining the prognosis of a tooth. In a retrospective study of 102 patients (816 molars) undergoing regular periodontal therapy, Miller et al. assigned scores to all teeth on the basis of periodontal prognostic factors. They determined that of all the factors evaluated, smoking had the most negative impact (246 % greater chance of losing their teeth), far exceeding the impact of pocket depth, mobility, or furcation involvement. The authors also mentioned that 78.3 % of the molars treated were never extracted and survived for an average of 24.2 years, which indicates that under preventive maintenance therapy, periodontal health can be maintained (Miller et al. 2014). One limitation of the study resides in the fact that the severity of the furcation involvement was not assessed; only its presence or absence was considered. However, it is understood by dental health professionals that the more severe the furcation involvement, the more difficult it is for the patient to maintain proper dental hygiene. The same could be said about pocket depths in excess of 3 mm. Surgical periodontal therapy could be indicated to reduce the pocket depth and increase the likelihood of dental hygiene to be effective.

Another prospective study on 100 treated periodontal patients under maintenance care (2509 teeth) was carried over a period of 16 years in an attempt to determine the effectiveness of commonly taught clinical parameters utilized in the assignment of prognosis to accurately predict tooth survival. The study concluded that initial probing depth, initial furcation involvement, initial mobility, initial crown-to-root ratio and parafunctional habit with no biteguard were all associated with tooth loss (McGuire and Nunn 1996). Teeth that were used as abutment for fixed partial dentures (FPDs) were lost at a lower rate than those who served the same function for removable partial dentures (RPDs). Interestingly, the authors suggested that the reasons that FPDs may have greater survival rate might be related to the initial choice of the tooth as an abutment, as only very healthy teeth would be used for a fixed abutment.

Multiple authors have reported that periodontal reasons are the most common cause for extraction of endodontically treated teeth with 59.4 % and 42.6 % of all extracted teeth (Fonzar et al. 2009). In esthetically challenging situations, with the presence of apical periodontitis, or when retreatment is needed, extraction of the tooth followed by implant placement has been recommended (Setzer and Kim

2014). However, as discussed above, if proper periodontal treatment is rendered, even on teeth with moderate vertical bone loss or furcation involvement, the prognosis could be good (Setzer and Kim 2014).

Any tooth is just as strong as its weakest link. If its foundation is compromised, its entire outcome also is. Besides a dental emergency, periodontal health has to be achieved and maintained before any treatment is to be initiated. As we will discuss later, when it comes to mechanical forces, a tooth is subjected to stresses that come from all directions. The weaker the support it has from its periodontium, the more likely the horizontal stresses on the entire system are to increase and the more strain the restoration and the periodontium have to absorb. Distribution of stress being a cornerstone concept in prosthodontics, the clinician must consider, when dealing with a less than ideal, yet healthy, periodontium to lighten the occlusion in eccentric movements. For example, when restoring a canine with a compromised, yet acceptable, crown-to-root ratio, the clinician should consider a group function rather than a canine guidance.

3.3 Tooth Restorability

For a comprehensive treatment plan to be formulated and before using the treatment planning flowchart in Fig. 3.2, a complete evaluation of the mouth along with that of the particular tooth in question is necessary. The clinician must evaluate the overall periodontal support, the occlusal scheme, and the presence or absence of parafunction. With regard to the occlusal plane in a comprehensive treatment plan, a tooth that has extruded and is not in harmony with the occlusal plane might not allow enough vertical space for an antagonist. For this tooth to be restored, the plan might involve the possibilities of orthodontic intrusion or crown lengthening with or without root canal therapy (see Fig. 3.3). Also, when it comes to the tooth in question, one must evaluate the quality of the root canal treatment. The latter is still a major cause of failure, as reviewed in Chap. 1.

A tooth serving as an abutment for an FPD or an RPD is subject to different stresses than if it were to support a single restoration. Lastly, if the possibility of crown lengthening is considered, the clinician must keep in mind some considerations for the crown-to-root ratio, the taper of the root, and the location of any furcation.

3.3.1 Evaluation of the Remaining Tooth Structure

Some clinical conditions (e.g., a vertical root fracture or an infraction that extends far apically into the periodontium) could justify the extraction of the affected tooth, particularly if the patient is not keen on the clinician performing an explorative surgery to determine its restorability. Other, less dramatic scenarios require the removal of carious dentin and/or defective restorations in order to properly assess the overall condition of the tooth (Fig. 3.4). It is following this step that we would

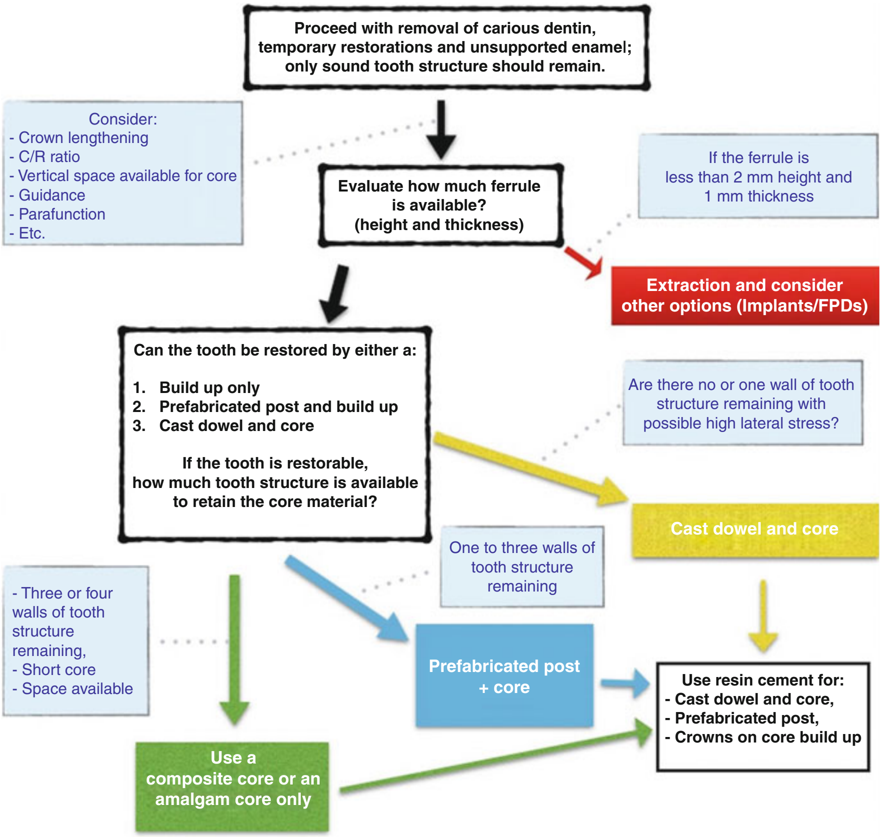

Fig. 3.2 This is the treatment plan flowchart that is referred to throughout this chapter

determine if the margin placement of the intended prosthesis is violating biologic principles (see the concept of biological width in Chap. 1, Fig. 1.2) and if the remaining sound tooth structure is sufficient in order to provide a strong support that will confer the restoration longevity and function. It is also at this stage that we assess the crown-to-root ratio and the occlusal forces the tooth is subject to in the dentition and determine the necessity of crown lengthening (Fig. 3.2).

3.3.2 Ferrule

Following excavation of carious dentin and removal of defective restorations, it is essential that sound tooth structure remains circumferentially to produce a cervical ferrule. Please refer to Chap. 1 for more detailed explanation about the ferrule concept.

If the condition of the tooth is such that even adjunct surgical and/or orthodontic procedures cannot provide a 2 mm-high ferrule, without compromising significantly

Fig. 3.3 This photograph shows the right mandibular second molar (mirror image) that has supra-erupted into the opposing edentulous space. Several years after its extraction, this patient is considering replacing his maxillary missing right maxillary first molar. An interdisciplinary approach, possibly involving orthodontic movement and/or crown lengthening and/or endodontic therapy, has to be considered to bring this tooth into the normal occlusal plane

Fig. 3.4 Several of these teeth would be deemed unrestorable even without removing the carious dentin and defective restorations. If crown lengthening is performed to obtain adequate ferrule on sound tooth structure, with or without endodontic therapy, the crown-to-root ratio becomes compromised. Considering the taper of the roots, the tooth preparation for any type of complete-coverage crown might result in very thin residual dentin walls

the prognosis of the tooth, extraction might be the solution (Fig. 3.4). When extensive tooth structure is lost after carious dentin or a faulty restoration are removed, or following trauma or endodontic access, but that the ferrule is at least 2 mm high and 1 mm thick, the clinician must consider the fabrication of a foundation prior to tooth preparation for complete-coverage restoration. In some cases, the tooth breakdown is so extensive that it could be in proximity to the pulp. These scenarios might necessitate an elective root canal treatment and the buildup of a core. The latter will increase the retention and resistance form of the future restoration.

According to Hempton and Dominici (2010), most of the retention and resistance to dislodgment of the restoration occurs at the apical third of the preparation. Therefore, the positioning of the margin remains of crucial importance. The clinician must avoid placing the margin if it is to be seated partially or completely on the core buildup. This precaution must be taken in order to avoid the stresses from occlusion to be transmitted to the foundation restoration or, in the case of a post and core, to the internal aspect of the post and the root. That interface is usually filled with cement, and, under occlusal stress, the fatigue of the cement could lead to dislodgment of the post and core or to the fracture of the tooth. In an in vitro study, Pilo et al. (2008) suggested that having a minimum thickness and length of ferrule is very important to prevent fractures. They explained that, in case fractures occur, they do so in the tooth structure, not in core material. Also, the potential of the teeth to fracture is directly related to the amount of dentin removed.

3.3.3 Dentin and Enamel Integrity

Worthy of mention, careful attention must be taken when instrumenting the canal during endodontic therapy as well as when preparing a post space. Over-instrumentation will contribute to over-enlargement of the root canal and unnecessary dentin removal. It is well accepted that a minimum of 1 mm of dentinal thickness wall is necessary to prevent its fracture and properly support the core foundation, if any is planned (Ouzounian and Schilder 1991).

As it was discussed in the previous chapter, mechanical properties of endodontically treated teeth could confer the dentin of the tooth different mechanical properties. However, it has been suggested that the type of cavity preparation could play an even more significant impact on cuspal deflection (separation of the cusps). In one study, it has been determined that intact mandibular molars had a cuspal deflection of up to 1.0 μm. As for MO cavity preparations, the deflection was noted to less than 2 μm of movement. MOD preparations showed a movement of 3–5 μm. Endodontic access preparations were responsible for a movement of 7.0–8.0 μm for the MO group and 12.0–17.0 μm for the MOD group (Panitvisai and Messer 1995). It has been advocated that maintaining the continuity of enamel maintains the tooth rigidity; henceforth, consideration should be given to some sort of cuspal protection, particularly when there is an increase of twofold or threefold from the MO to the MOD group with endodontic access preparation.

It seems that the mechanical properties of the endodontically treated tooth's dentin might not be as critical as the initial appearance of the tooth that lead to the endodontic treatment. The integrity of the enamel seems to play a more important role than whether or not it has been treated endodontically. In the next section, we will have a closer look at the literature when it comes to the impact of such results on the overall outcome of the tooth.

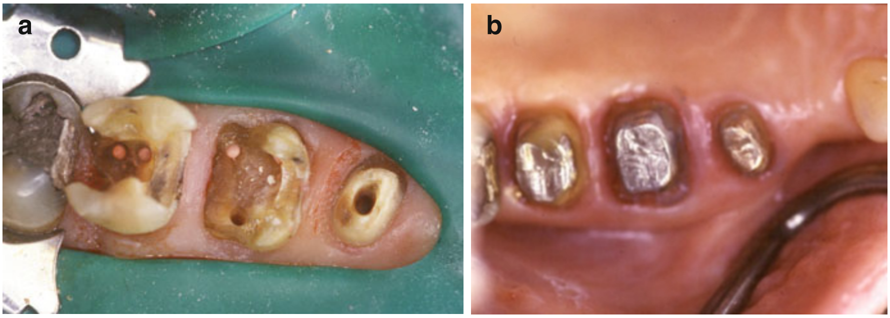

Fig. 3.5 (**a**) After removal of the carious dentin and defective margins, the remaining tooth structure on the maxillary right second premolar is insufficient to retain a core and is not strong enough to resist crown fracture at the neck of the tooth. As for the maxillary right first molar, it has fewer than three walls left and would need a post to retain a core. On the other hand, the maxillary right second molar has sufficient walls left to retain a core and resist crown fracture at its neck. (**b**) A cast dowel and core was placed on the maxillary right second premolar, a prefabricated metal post was inserted into the palatal root of the maxillary right first molar, and an amalgam core was built. As for the maxillary right second molar, an amalgam core was used to rebuild the missing tooth structure

Let us go back to the treatment planning flowchart (Fig. 3.2). After determining the stress that will be applied to that tooth, we need to answer two questions: (1) Is there enough remaining sound tooth structure to retain a core? and (2) Is the remaining tooth structure strong enough to resist crown fracture at the neck of the tooth? If the answer to both these questions is "no," then a cast dowel and core or a prefabricated post and core buildup are to be considered. If the answer to both questions is "yes," then a (composite resin or amalgam) core restoration buildup should be considered (Figs. 3.2 and 3.5).

In a randomized clinical trial on 360 premolars followed up for 3 years, Cagidiaco et al. (2008) divided the teeth in six groups of 60 premolars based on the amount of the dentin left at the coronal level after endodontic treatment and before abutment buildup. They then randomly assigned them into subgroups with or without fiber posts. They determined that a (fiber) post might not be needed in four coronal walls situation but that as soon as we lost one wall, we started seeing failures in the groups with no post. In the post group, failures increased in the group with one coronal wall and the groups with no wall with or without a 2 mm ferrule. Two studies by Ferrari et al. (2007, 2012) also confirmed that the placement of a fiber post reduced significantly the failures on endodontically treated premolars. The preservation of one coronal wall significantly reduced the failure risk.

In situations of three or four coronal walls remaining, one must choose between different core materials. In a fatigue study, Kovarik et al. (1992) tested glass ionomer cement (GIC), composite resin, and amalgam as a core material under crowns. It took 20,000 cycles to bring all GIC core crowns to failure. At 50,000 cycles, 80 % of composite core crowns experienced failures. As for amalgam core crowns, 30 % experienced failures at 70,000 cycles. Gateau et al. (2001) reported that two GIC-based materials used as core materials showed a higher number of defects than amalgam, suggesting that fatigue resistance of GIC-based materials may be inadequate for post and core applications. Some clinicians have used silver-reinforced GIC-based materials (known as cermets) for core buildups. As stated by Combe et al. (1999), cermet GIC materials are one of the weakest materials in terms of tensile, flexure, and modulus values, despite being similar to some resin materials in terms of compressive strength. Cermet GIC materials are not suitable for core buildup procedures in the posterior teeth.

3.4 Prognosis of Endodontically Treated Teeth

Restorative considerations put aside, endodontic therapy has been demonstrated to be a predictable procedure provided that the quality of the canal disinfection and that of the root canal obturation are good. In the absence of preoperative apical periodontitis, primary root canal therapy has shown success rates above 90 % (Marquis et al. 2006). However, when preoperative apical periodontitis was present, this number dropped to approximately 80 % (Sjogren et al. 1990; de Chevigny et al. 2008).

In their systematic review, Gillen et al. (2011) suggest that all aspect of the treatment, from the periodontal condition to the root canal therapy to the restoration, have an impact on the overall outcome. When coronal restorations are inadequate, the odds of maintaining the healed status of an apical periodontitis decrease as microbes ingress through the defective margins of the restorations.

3.4.1 Survival Rate of the Endodontically Treated Anterior Teeth

There is a belief that endodontically treated anterior teeth without crowns are not susceptible to as much fracture as posterior ones. However, a recent study on 1.4 million teeth (Salehrabi and Rotstein 2004) demonstrated that 83 % of teeth that were extracted had not received a crown, while 9.7 % of the extracted teeth had a crown and a post and 7.3 % of the extracted teeth had a crown without post. The result of this 2004 large-scale study contrasts the findings reported by Sorensen and Martinoff in 1984, where it was suggested that endodontically treated anterior teeth do not have a significantly better prognosis if they are crowned, compared if there were not (Sorensen and Martinoff 1984). Please refer to Chap. 6 for more evidence about the positive impact of fiber posts on endodontically treated anterior teeth.

3.4.2 Survival Rate of the Endodontically Treated Posterior Teeth

When endodontically treated posterior teeth are not restored with a crown, they are more likely to fracture than vital teeth (Aquilino and Caplan 2002). In another study, it was demonstrated that teeth without crowns failed after an average period of

50 months, while pulpless teeth restored with a full coverage restoration were lost after an average of 87 months following the placement of the restoration (Vire 1991). In a retrospective cohort study, it was demonstrated that endodontically treated molars that were intact, except for the endodontic access opening, were successfully restored using composite resin restorations. It is interesting to know that composite resin restorations had better clinical performance than dental amalgam restorations. On a 2-year basis, the survival of molars restored with composite resin restorations was 90 % vs. 77 % for amalgam restorations. At 5 years, the survival declined significantly for both restorative materials, to 38 % for composite resin and 17 % for dental amalgam restorations (Nagasiri and Chitmongkolsuk 2005). Similarly, a 3-year investigation found comparable success rates between endodontically treated premolars restored with only a post and direct class II composite resin and premolars restored with complete-coverage crowns (Mannocci et al. 2002).

Amalgam may be used provided all cusps adjacent to teeth with missing marginal ridges are covered and sufficient thickness of amalgam is present, as seen in Chap. 1. It has been recommended that a thickness of 4.0 mm of amalgam protects the functional cusp and 3.0 mm over the nonfunctional cusp (Liberman et al. 1987).

Once we have determined the restorability of the tooth as a unit, it is important to assess the stress that will be applied to that tooth. As we will discuss in the next section, there is scientific evidence that suggests that an endodontically treated tooth's position in the arch as well as its future function has an impact on its survival rate. Also Chap. 6 covers the impact of placing fiber posts on the longevity and prognosis of posterior endodontically treated teeth.

3.4.3 The Importance of Proximal Contacts

It has been determined that the presence of two proximal contacts had a significant positive impact on the survival rates of endodontically treated teeth (Aquilino and Caplan 2002; Caplan et al. 2002). Caplan et al. (2002) performed a retrospective study in which they reviewed charts and radiographs of 400 teeth from 280 patients. They suggested that endodontically treated teeth with less than two proximal contacts underperform the ones with two proximal contacts. To reinforce that point, a meta-analysis of 14 clinical studies also pointed out that observation. In descending order of influence, the conditions increasing the survival rate of endodontically treated teeth were as follows: (1) a crown restoration after RCT, (2) tooth having both mesial and distal proximal contacts, (3) tooth not functioning as an abutment for removable or fixed prosthesis, and (4) tooth type or specifically non-molar teeth (Balto 2011).

Another 4-year prospective study involving 759 primary root canal-treated teeth and 858 endodontically retreated teeth demonstrated that teeth with two proximal contacts had a 50 % lower risk of being lost than those with less than two proximal contacts. It was demonstrated that terminal teeth were associated with almost 96 % more tooth loss than those that were not located distal most in the arch (Ng et al. 2011). In a 10-year follow-up study, Aquilino and Caplan demonstrated that second molars had a significantly lower survival rate than any other type of teeth. The greater than fivefold decrease in the endodontically treated second molar's survival rate could be explained by the result of increased occlusal stresses and difficult endodontic treatment due to a compromised access and restricted visibility (Aquilino and Caplan 2002).

It is well documented that the position of the endodontically treated tooth in the arch and the presence or absence of proximal contact have a significant impact on its survival rate. This could be explained by the unfavorable distribution of occlusal forces and higher non-axial stress on these teeth. Also, regardless of the chewing forces of the patient, an endodontically treated tooth is better off, in terms of stress, to oppose an acrylic tooth from a complete conventional denture than it is to oppose a single implant crown. It has more to do resiliency of the opposing prosthesis than it is about the material.

3.4.4 FPDs and RPDs

Multiple clinical studies have suggested that FPDs supported by endodontically treated abutment teeth fail more often than those supported by vital abutment teeth (Reuter and Brose 1984; Karlsson 1986; Palmqvist and Swartz 1993; Sundh and Odman 1997). Over 20 years ago, Sorensen and Martinoff (1985) reviewed over 6000 patients' records, and based on 1273 teeth endodontically treated that served as an abutment for either an FPD or an RPD, they concluded that abutments for FPDs and RPDs that were endodontically treated had significantly higher failure rates than single crowns. Respectively, the success rate of all endodontically treated RPD abutments was 77.4 % compared with FPDs, which was 89.2 %. Interestingly, they also found that post placement was associated with significantly decreased success rate for single crown, produced no significant change for FPD abutments, and significantly improved the success of RPD abutment teeth. The nature of the study being retrospective, variables that were not recorded and may have affected that function of the RPD, and stresses on the endodontically treated teeth include the rest and retainer design, the quality of the adaptation of the extension bases, and the occlusion. Also, the span of the distal extension was not recorded, and no distinction was made between a tooth-borne and a distal extension RPD.

A more recent clinical study compared FPDs and single crowns for up to 20 years. The authors reported that the survival rate of three-unit FPDs with at least one endodontically treated abutment was comparable to FPDs on vital teeth. More failures were associated with FPDs with cantilevered units and those with more than three units (De Backer et al. 2007). Once again, when considering an endodontically treated tooth as an abutment for a prosthesis, one must accord crucial importance on the antagonist prosthesis, if any, on the periodontal condition and bony support, as well as the amount of stress bearing the abutment will be subject to. The clinician's judgment plays an important role when, for example, he/she is confronted to a situation where a three-unit posterior FPD is retained by two endodontically treated abutments opposing a stable complete conventional denture and another situation where a nonterminal single endodontically treated and crowned posterior tooth is opposing an implant crown. The literature does not have any answer for which of the two scenarios is more favorable on the endodontically treated tooth.

3.5 Adjunct Surgical Procedures

3.5.1 Biologic Width

When carious dentin, cavitation, or existing restorations are extensive and in proximity with the root and that crown lengthening is planned, the biologic width (Fig. 1.2, Chap. 1) has to be considered. If it is violated, it may induce chronic inflammation (Gunay et al. 2000) and even lead to periodontal breakdown (Cunliffe and Grey 2008). Gargiulo et al. (1961) published one of the first studies on the issue of the dimensions of the biologic width. They averaged the length of the dentogingival junction to be 2.04 mm, the epithelial attachment to be of a mean value of 0.97 mm, and the connective tissue attachment to be of a mean value of 1.07 mm.

When it comes to restoration margin placement, some authors have advocated the importance of maintaining a 3 mm biologic distance coronal to the osseous crest and the plaque-associated margins (Nevins and Skurow 1984). Another retrospective study indicated that 40 % of the molars developed a furcation lesion at 5 years after the crown placement if their initial margin-to-bone distance is less than 4 mm (Dibart et al. 2003).

Although it seems to be widely accepted that a minimum of 3 mm from the osseous crest to the restoration margin significantly reduced the risk of periodontal attachment loss, the clinician must always keep in mind that every patient's dental anatomy is slightly different. Vacek et al. (1994) tested a hypothesis similar to that of Gargiulo et al.'s previous study and published a range of biologic width (Table 3.1). Adequate probing and proper diagnostic radiographs are invaluable.

When in doubt, it is typically because we are about to violate the biologic width. However, if one wishes so, a long-term provisional restoration could be a good method to test the response of the epithelial attachment prior to deciding on crown lengthening. Careful attention must be taken to have tight margins and a well-polished provisional restoration to prevent marginal leakage and/or accumulation of inflammation-inducing plaque.

Table 3.1 Range of biological width, as published by Vacek et al. (1994)

Biologic width (EA + CTA) (Vacek 1994)		
Arch position	Measurement	Range
Anterior	1.75 ± .56	.75–3.29
Premolar	1.97 ± .67	.78–4.33
Molar	2.08 ± .55	.84–3.29

Fig. 3.6 In this clinical presentation, the inflammation of the gingival tissue is evident. The retainer's margin of this FPD (9-X-11) has clearly violated the epithelial attachment. The clinician must keep in mind the gingival margin level of the contiguous teeth if crown lengthening is to be performed. Forced orthodontic extrusion, combined with crown lengthening, could be considered

3.5.2 Crown Lengthening

When the tooth presents with little structure to allow for retention and resistance on sound dentin, the clinician might need to "create" additional sound tooth structure by reverting to surgical procedure. The crown lengthening surgical procedure might need to be combined with orthodontic forced eruption (Fig. 3.6). We will not be discussing the details of orthodontic forced eruption in this chapter. The reader who is interested will find a great deal of information on the subject in other dental literature. The addition of sound tooth structure to be embraced by the future restoration allows for the occlusal forces to be distributed into the periodontium rather than on the post-core-tooth interface. However, one must keep in mind the crown-to-root ratio as the mobility of the tooth could increase and accentuate the amount of horizontal components to the occlusal stress. The inertia of the periodontal membrane to an axial load has been calculated as being 17 times as great as it is to a transverse load (Thayer 1980). Al-Hazaimeh and Gutteridge (2001) tested in vitro the effect of a ferrule preparation on the fracture resistance of ten post crowned natural central incisor teeth with a 2 mm ferrule preparation and compared it to his control group of ten without ferrule. The author suggested more attention be given to the post length than the presence of a ferrule.

The need for the future restoration to embrace sound tooth structure circumferentially in order to increase its resistance to fracture cannot solely justify the creation of a ferrule through surgical procedure. Along with the overall treatment plan, other considerations have to be taken into account during treatment planning.

In order to remain favorable, the crown-to-root ratio must remain at a maximum of 1:1. Considering that the reduced periodontium is still subjected to the same amount of load, increased mobility could result from poor planning. Also, when roots are in near proximity, it becomes difficult to remove the interdental bone without damaging the roots. This will also result in a limited crown exposure since the soft tissue cannot be repositioned apically.

The clinician must keep in mind that the further apically the preparation of the tooth, the thinner the dentinal wall is and more likely the chances of pulp exposure or of over-contouring of the restorations due to insufficient restorative space laterally. The clinician must be diligent in choosing the appropriate finish line, particularly in the lower anterior teeth (Borelli et al. 2015).

Fig. 3.7 Despite adequate ferrule and respect of other resistance and retention principles, biologic principles like the lack of attached gingiva are evident around the preparations of these right maxillary premolars

In order to maintain periodontal health and prevent the creation of a mucogingival defect, it is important that the amount of attached gingiva remains at least 2–3 mm (Fig. 3.7) (Maynard and Wilson 1979).

Finally, the clinician must keep in mind the entire dentition and the overall treatment plan. In an esthetically driven patient, or with patient with a high smile line, the patient's lip position could reveal a disharmony between the gingival levels and affect the esthetic outcome. In cases of passive eruption in the anterior region, the short clinical crowns sometimes accompanied by a high smile line could result in excessive gingival display. If the patient is concerned about having teeth with better proportions in the anterior sextant, surgical crown lengthening exposing more anatomical crown might be warranted (Allen 1993; McGuire 1998). In these scenarios, a diagnostic wax-up must be completed in order to provide the surgeon with a surgical stent to properly determine the position of the new restorations. Functional and esthetic crown lengthening can be combined when subgingival caries do not extend apically into the root. Also particular care must be taken due to the possible loss of the interproximal papillae. One must determine whether there is a need for resective surgery of the interdental bone or whether it should be limited to the labial aspect. In the advent that the gingival embrasures are widened, resulting in an unpleasant display, the restorative dentist might need to better contour the restorations or widen their contact area. Black triangles can develop where the distance between the interdental osseous crest and the contact point is greater than 5 mm (Tarnow et al. 1992) (Fig. 3.8).

3.6 Treatment Options for Missing Teeth

When one or several teeth are deemed unrestorable or have poor prognosis, extraction is often the outcome. The patient has to be informed of the diagnosis and the rationale prior to discussing replacement options.

Fig. 3.8 (**a**) The provisional crowns on the maxillary right lateral incisor, the maxillary right central incisor (implant), the maxillary left central incisor, and the maxillary left lateral incisor were left in the mouth for approximately 6 months to allow for the papillae to creep into the gingival embrasures. (**b**) Ultimately, crown lengthening only on the labial aspect of the maxillary left central incisor and proper contouring of the permanent restorations created an esthetically pleasing result (Courtesy of Dr. Remi Elkattah and master ceramist Aram Torosian)

3.6.1 FPDs

For many years, FPDs have been considered the gold standard. They are relatively quick to fabricate and provide a reasonable and a somehow predictable result. Undeniably, their downfall is the preparation of the adjacent teeth and their difficulty to clean. It is more likely the noncompliance of the patient to perform oral hygiene under the pontic than their difficulty to clean that affects their survival rate and increases the risk of decay around the margins of the restoration. Although some cases of bone deposition under pontics have been reported, the lack of stimulation of the alveolar bone by the periodontal ligament under pontics most often results in bone loss and the need of the restorative dentist and the dental technician to fabricate bigger than normal pontic height or to mask the defect with pink porcelain.

Several authors have written on the longevity of FPDs. Salinas et al. (2004) have reported a 69 % survival rate at 15 years. Others have suggested a 50–69 % survival rate at 20 years (Budtz-Jorgensen 1996). The survival of adjacent teeth at 10 years has been reported at 92 % (Aquilino et al. 2001). A proper solution is only one that complies with evidence-based dentistry and meets the patient's expectations. Henceforth, the patient is presented with other treatment modalities to replace an edentulous area.

3.6.2 RPDs

An RPD is a relatively inexpensive tooth replacement alternative and has the potential to replace areas where the soft tissue is deficient in volume. Unfortunately, patients sometimes report the sensation of having a "mouthful." Also, depending on the clinical situation, removable partial dentures could represent significant torque/stress on adjacent teeth, and being partially supported by the underlying tissue, bone loss is to be expected under the load-bearing areas. The longevity of this type of prosthesis at 10 years has been reported at 50 % (Budtz-Jorgensen 1996). Aquilino et al. (2001) reported a 56 % survival rate at 10 years for the teeth adjacent to the edentulous areas.

3.6.3 Endosseous Dental Implant

Taking over FPDs as the gold standard for replacing edentulous areas, dental implant restorations help maintain bone in edentulous spaces by stimulating the bone. Although this alternative often requires a longer treatment time, involves surgical procedures, and represents an initial increased cost, the adjacent teeth remain more often than none untouched and the long-term financial investment is considerably reduced. Although dental caries are not a concern for implant restorations, new concepts of peri-implant mucositis and peri-implantitis have surfaced with the advent of implants. Wilson has reported cases of cement-induced peri-implantitis manifesting as long as 9 years after the insertion of the final cement-retained prosthesis (Wilson 2009). On the other hand, several studies have demonstrated endosseous dental implant survival rate of above 95 % on 15–20 years (Budtz-Jorgensen 1996; Salinas et al. 2004).

From a prosthetic point of view, the presence or absence of the periodontal ligament makes a significant difference in tactile sensitivity between implants and natural teeth. The mean values of an axial displacement of teeth are approximately 25–100 μm, compared with a dental implant of 3–5 μm (Schulte 1995; Kim et al. 2005). The dental implant restoration and its components are therefore subject to more stress, and the periodical evaluation of the occlusion is of utmost importance to prevent fracture or chipping of the ceramic or technical/mechanical complications of the implant restoration system. In a 10-year retrospective study assessing the rate of mechanical/technical complications and failures with implant-supported fixed dental prosthesis and single crowns, Wittneben et al. (2014) demonstrated that out of 397 fixed implant reconstructions, ceramic chipping was the most frequent complication (20.31 %) followed by occlusal screw loosening (2.57 %) and the loss of retention (2.06 %).

Dental implants could play a role in preserving remaining teeth; Priest has reported a 99.5 % survival rate of the adjacent teeth on a 10-year period (Priest 1999).

Finally, if it is the patient's wish to do so, an edentulous space could remain so. Inevitably, this could lead to bone loss in the edentulous area and affects the survival of the adjacent teeth (Aquilino et al. 2001).

3.7 Summary

In a very concise way, here is the thought process leading to the treatment planning:

The clinician must perform a complete evaluation of the whole mouth, in tandem with the particular tooth in question, so that a clear and comprehensive treatment plan can be formulated.

1. How are the current condition and the prognosis of the tooth?
   (a) Periodontal support
   (b) Quality of root canal treatment
2. How much of sound tooth structure will remain after?
   (a) Caries removal
   (b) Root canal treatment
   (c) Crown preparation
3. How much of stress will be applied to that tooth?
   (a) Serving as a single crown vs. abutment of FPD/RPD
   (b) Enduring eccentric guidance
   (c) Occlusal force (anterior vs. posterior tooth), bruxism/clenching
4. After knowing the structure and stress issues, ask the following questions, while considering how much vertical space exists for core buildup.
   (a) Is the remaining sound tooth structure sufficient to provide a strong support to the restoration? (sub-question: Will post improve the retention of the core?)
   (b) Is the remaining tooth structure strong enough to resist crown/core fracture at the neck of the tooth? (sub-questions: Pocket depth? Is crown lengthening possible and worth it? Will bonded post strengthen the system?)

If the answers of the two questions are:

YES, the options are:

1. Amalgam or composite core restoration (four, three, two remaining walls) (sub-question: Will composite core bonding against amalgam lower the chance for cusps split?)
2. Prefabricated post (three, two remaining walls) + core buildup (sub-questions: If vital, is elective endodontic treatment worth it? Even with enough tooth walls, will addition of fiber post improve prognosis of the tooth?)
3. Prefabricated post, if maxillary anterior teeth had an endodontic treatment and crown is indicated

NO, the options are:

1. Prefabricated post (three, two, one wall) + core buildup (sub-question: If vital, is elective endodontic treatment worth it?).
2. Cast dowel and core (one wall or ferrule only or compromised ferrule) (sub-question: If vital, is elective endodontic treatment worth it?).

3. Crown lengthening + cast dowel and core (sub-question: If vital, is elective endodontic treatment worth it on top of crown lengthening?).
4. Extract and replace tooth with implant or FPD.
5. Finally, consider overall treatment plan of full dentition, the longevity of treatment, other options that might be available (implant, FPD, RPD), cost effectiveness, what patient wants, etc.

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Fiber-Reinforced Dental Materials in the Restoration of Root-Canal Treated Teeth

4

Johanna Tanner and Anna-Maria Le Bell-Rönnlöf

Abstract

Fiber-reinforced composites (FRC) are a group of lightweight metal-free dental materials characterized by their anisotropic nature. They are relatively low-cost, tooth-colored materials that are compatible with the use of adhesive and direct restorative techniques. Contemporary dental FRCs are predominantly based on glass fibers and dimethacrylate resins. For optimal clinical performance, it is crucial that the properties and behavior of these composite materials are well understood. In an FRC, the fibers provide strength and stiffness, while the matrix polymer binds the fibers together, forming a continuous phase around the reinforcement. For optimal mechanical properties, the fibers must be well adhered to and well impregnated by the matrix polymer. Other factors influencing the mechanical, optical, and bonding properties of FRCs include the type of fiber and matrix polymer, quantity, positioning, and orientation of fibers. Contemporary dental FRCs can be based on either unidirectional or multidirectional long continuous fibers or short discontinuous fibers. FRCs offer several benefits in restoring root-canal treated (RCT) teeth. Elastic modulus close to that of natural dentin, high tensile strength, and the suitability for cost-effective chairside techniques make fiber-reinforced composites well suited in the restoration of structurally compromised RCT teeth.

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4.1 Introduction to Fiber-Reinforced Composites in Dentistry

Fiber-reinforced composites (FRC) are lightweight metal-free materials characterized by good mechanical properties, such as high fatigue resistance and fracture toughness. Modern fiber-reinforced composites are used in applications where high static and dynamic strength as well as fracture toughness is required. Fiber-reinforced composites are widely used in industrial applications, such as sports equipment and boat hulls. The first dental applications date as early as 1960s, when fiber reinforcements were reported to be used in reinforcing denture base acrylics (Smith 1962; Schwickerath 1965). Improvements in the handling properties of fiber reinforcements in the 1990s have finally brought FRCs into the field of dental materials in a larger scale.

FRCs were first mainly used to reinforce acrylic base materials of removable dentures (Ladizesky et al. 1992; Vallittu 1997a; Cheng and Chow 1999). Their reinforcing effect was found to be superior to that of conventional metal wire strengtheners (Vallittu 1996). When reinforcing fibers were successfully combined with dimethacrylate resins and particulate filler composites, they became applicable in fixed prosthodontics and other fields of dentistry as well. Literature reports the use of FRCs as fixed partial dentures (Freilich et al. 1998a, b; Behr et al. 2000; Meiers and Freilich 2000; Vallittu and Sevelius 2000; Ahlstrand and Finger 2002; Göhring et al. 2002; Kolbeck et al. 2002), implant suprastructures (Freilich et al. 2002; Meiers and Freilich 2006; Ballo et al. 2009; Zhao et al. 2009), periodontal splints (Meiers et al. 1998; Sewón et al. 2000), and orthodontic retainers (Rantala et al. 2003; Kirzioĝlu and Ertük 2004). Applications of FRCs in restorative dentistry include root canal posts (Mannocci et al. 1999a, b; Qualthrough et al. 2003), repairs of fractured porcelain veneers (Valittu 2000; Özcan et al. 2006), and reinforcement of restorative composites (Fennis et al. 2005; Garoushi et al. 2013). The use of an adhesive technique, together with the possibility to tailor the physical properties of the restorations through individual fiber orientation and positioning, makes FRC restoration a minimally invasive, tooth-conserving technique. Other benefits promoting the use of FRC materials are their cost-effectiveness and, in the case of glass- and silica fibers, good cosmetic properties due to the translucency of the fibers. A critical evaluation of the FRC materials available and the correct patient selection is of high significance to ensure the successful use of these materials.

4.2 Fiber-Reinforced Composites: Structure and Properties

A fiber-reinforced composite consists of reinforcing fibers embedded in a polymer matrix. In contrast to particulate fillers, typically used in dental restorative composites, FRCs are reinforced with high-aspect ratio fillers. Their length being much greater than their cross-sectional dimensions characterizes this type of fillers, typically fibers or whiskers. In a fiber-reinforced composite, the fibers provide strength and stiffness, while the matrix polymer binds the fibers together, forming a continuous phase around the reinforcement. This phase transfers the loads to the fibers and protects the fibers from the moisture of the oral environment. For optimal mechanical properties, the fibers must be well adhered to (Beech and Brown 1972) and well impregnated by the polymer (Vallittu 1995a). Impregnating fibers with high-viscosity resin systems, such as denture base acrylics or particulate filler composites, is difficult. If complete impregnation is not achieved, for example, due to high viscosity or polymerization shrinkage of the resin, optimal mechanical properties cannot be reached (Vallittu 1998a). Preimpregnation of fibers by the manufacturer is therefore needed to ensure proper impregnation. In addition to the interfacial adhesion, several other parameters, such as fiber elongation and fiber volume fraction, influence the reinforcing effect of fibers in a composite.

The type, positioning, and orientation of reinforcement largely determine the mechanical properties of the composite (Murphy 1998). Depending on the design of the composite, the reinforcing fibers can be either unidirectional, running all parallel to each other, or multidirectional, oriented in two or more directions. The higher the fiber concentration, i.e., the fiber volume fraction, the higher is the tensile strength of the composite. A relatively small quantity of fibers may however be sufficient, given that it is positioned on the tension side of the composite structure. In dental applications, this concept of partial fiber reinforcement is often more applicable than a total fiber reinforcement (Vallittu and Narva 1997; Vallittu 1997a). The reinforcement is used in a high stress-bearing area and covered with a second material to fulfill the esthetic and hygienic needs. The end result is a reconstruction consisting of multiple phases, such as a post-and-core restored root canal-treated tooth. Strength and stiffness of all its parts and their adhesion to one another contribute to the performance of the whole.

4.2.1 Fiber Length and Orientation

When reinforcing fibers are oriented in the direction of stress, they provide the highest reinforcing efficiency. However, when stress is applied perpendicular to the long axis of the fibers, the fibers do not reinforce the polymer at all. The mechanical properties of FRCs depend on the direction of the long axis of the fibers. This property is known as anisotropicity. The efficiency of fiber reinforcement and its dependency on fiber length and orientation is described by Krenchel's factor (Fig. 4.1). Modification of fiber positioning and orientation allows for FRCs to be designed in a way that they can yield highest strength and reinforcing efficiency against the direction of stress. In addition to mechanical properties, optical properties, surface physical properties, and polymerization contraction properties of an FRC are related to fiber orientation.

FRCs can be described as short discontinuous FRCs or long continuous FRCs, according to the aspect ratio of the fibers used. A root canal post is a typical application of a long continuous FRC. Short discontinuous fibers can be used to reinforce dental filling composites (Garoushi et al. 2013). The mechanical properties of short and long FRCs differ from each other, while the fiber volume fraction remains the same (Kardos 1993). When continuous unidirectional fibers are replaced by longitudinally oriented discontinuous fibers of lower aspect ratio, the ultimate tensile strength

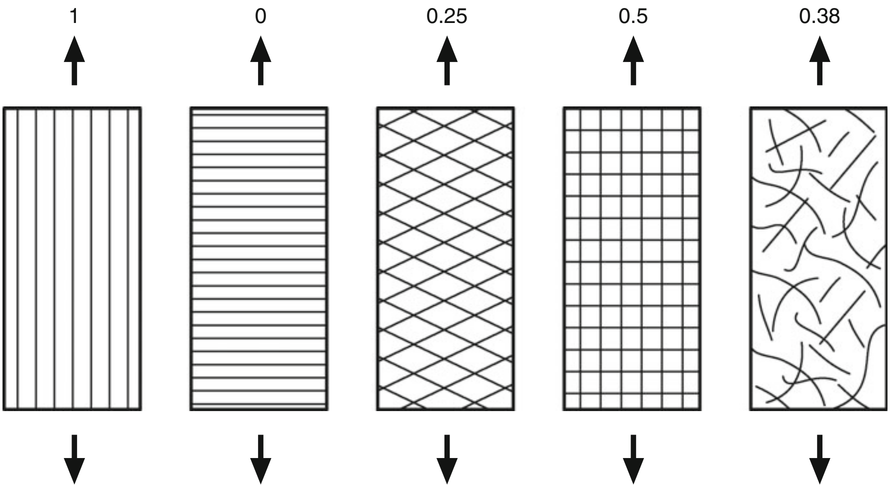

Fig. 4.1 Reinforcing efficiency, Krenchel's factor, of fibers according to their orientation. From left to right: Reinforcing efficiency of unidirectional fibers oriented in the direction of the load, 90 angle to the load, bidirectional fibers in 45/45 angle to the load, 0/90 to the load and short random fibers. *Arrows* show the direction of the load

of the composite is reduced, but the material still remains anisotropic (Fig. 4.1). If, instead, the short fibers are randomly oriented, the material becomes isotropic. At the same time, the tensile strength of the composite decreases further. Failure types of continuous and discontinuous FRCs differ from each other, as the high tensile strength of unidirectional FRCs cannot be obtained with discontinuous FRCs. Failure types of discontinuous short FRCs include cracking of the polymer matrix, debonding of the fiber, and fracture of the fiber, whereas axial tensile failure, transverse tensile failure, and shear failure are the most common failure types of unidirectional continuous FRCs (Vallittu 2015). Factors, such as fiber length, aspect ratio of the fibers, and adhesion of fibers to the matrix polymer, influence the failure types.

4.2.2 Fiber Type

In order for the fibers to have a reinforcing effect, their flexural modulus must be greater than that of the matrix polymer used (Murphy 1998). Several types of fibers have been tested and found to be applicable as reinforcements of dental polymers, most commonly glass, carbon/graphite, and polyethylene fibers.

Currently, glass fibers are the fibers most suitable for clinical dentistry. The benefits of glass fibers include high tensile strength, low extensibility, excellent compression and impact properties, and low cost. Their transparent appearance is also well suited for dental applications with high cosmetic demands, such as root canal posts in the anterior teeth. Yet, the most important factor behind the success of glass fibers is undoubtedly the surface chemistry, which allows for their adhesion to dental polymers via silane coupling agents. Glass fibers stretch uniformly under stress to their breaking point, and on removal of the tensile load short of breaking point, the fiber will return to its original length. This property, together with their high mechanical strength, enables glass fibers to store and release large amounts of energy (Murphy 1998). According to the chemical composition of the glass mass, the glass fibers are classified into A (alkali), C (chemically resistant), D (dielectric), E (electrical), R (resistant), and S (high strength) glass types. They differ in mechanical and chemical resistance properties. The most commonly used glass fiber in reinforced composites is E glass (99 % of all glass fibers manufactured) (Vallittu 1998b), which has a calcium-alumino-borosilicate composition. The developments in dental FRC technology, in terms of optimizing the fiber volume fraction and the properties of the polymer matrix, have resulted in relatively high flexural strength values (up to 1150 MPa) (Lassila et al. 2002; Alander et al. 2004) of unidirectional E glass fibers, comparable to those of cast cobalt-chromium alloy (1200 MPa) (Vallittu 1997b).

Carbon fibers, or carbon/graphite fibers, have been widely used in reinforced composites of high-performance applications. Carbon fibers are stronger than steel, lighter than aluminum, and stiffer than titanium (Murphy 1998). Mechanical properties of carbon fibers vary along with the composition, but generally carbon/graphite fibers exhibit very high strength in both tension and compression. The first dental application of carbon/graphite fibers was in reinforcing PMMA in the early 1970s (Schreiber 1971), which resulted in an increase in flexural strength of almost 100 %. The main drawback limiting the use of carbon/graphite fibers in dental applications is the black color of the fibers, as well as the difficulties in manufacturing and handling properties. The prefabricated root canal post has been the most widespread application of carbon/graphite fibers in dentistry (Isidor et al. 1996; Purton and Payne 1996; Torbjörner et al. 1996; Fredriksson et al. 1998).

Ultrahigh molecular weight (UHMW) polyethylene fibers are among the strongest reinforcing fibers available. They consist of aligned polymer chains with low-elastic modulus and density and offer good impact resistance (Murphy 1998). Their color is white and they are thus suited for dental applications. Several authors have investigated the reinforcing effect of polyethylene fibers on dental polymers (Ladizesky et al. 1990; Gutteridge 1992). Despite of excellent flexural properties of UHMW-polyethylene fibers, their clinical use is limited, mainly because of the problems involved in bonding the fibers to dental resins. Methods, such as plasma spraying, have been tested to improve adhesion, but the results have not been promising (Ladizesky et al. 1990). Additionally, the high affinity of proteins and oral microbes that adhere to the UHMW-polyethylene fibers may limit their use as dental materials (Tanner et al. 2003, 2005).

4.2.3 Bonding Properties

Like all composite materials, a fiber-reinforced composite consists of more than one type of material. In an FRC, the resin matrix, the fibers, and often also other inorganic fillers act as the bonding substrate. If the fibers are exposed on the surface, the adhesion properties of the fibers themselves play a role in adhering restorative composites or resin cements to the FRC. Glass and silica fibers can be bonded to dental resins by silanization and contribute thus in the bond strength of the composite structure (Vallittu 1993). Silane coupling agents promote adhesion through forming hydrogen bonds with the glass surface and covalent bonds with the methacrylate groups of dental resins (Matinlinna et al. 2004).

Adhesion to the other main component of the FRC, the polymer matrix, is mainly dependent on the type of resin system used. Contemporary dental resin systems are predominantly dimethacrylate based. In FRCs, both epoxy- and dimethacrylate-based matrices have been used. Most dental FRCs utilize resin systems based on bisphenol A glycidyl dimethacrylate (bis-GMA), triethylene glycol dimethacrylate (TEGDMA), and urethane dimethacrylate (UDMA). These thermosetting multifunctional resins form highly cross-linked polymer networks and are thus poor adhesive substrates in a dental office. For example, adhesion between the epoxy-based matrix of FRC post and resin cement is found to be mainly mechanical (Purton and Payne 1996). Some manufacturers have tried to overcome this problem by adding serrations in the surface of FRC posts.

Another approach to improve bonding properties is to alter the composition of the resin matrix of FRC by introducing a phase with a lower degree of cross-linking polymer chains. This type of multiphasic matrix polymer, containing a mix of thermoplastic and thermosetting polymer chains, is defined as a semi-interpenetrating polymer network (semi-IPN) (Sperling 1994). Impregnation methods of glass fibers based on a combination of thermoset and thermoplastic resins have been developed (Vallittu 1995b; Lastumäki et al. 2003). Adding linear polymer of polymethylmethacrylate (PMMA) to the matrix not only increases the toughness of the material (Lassila et al. 2004) but also increases its surface adhesive properties. The non-cross-linked thermosetting polymer chains (PMMA) allow the bonding resin monomers to diffuse into the previously polymerized matrix (Mannocci et al. 2005). Several authors have demonstrated the contribution of a semi-IPN structure to composite adhesion (Kallio et al. 2003; Lastumäki et al. 2003). Fiber-reinforced composite utilizing semi-IPN chemistry is used to fabricate root canal posts and a bulk-filling composite (see Sects. 4.3.1 and 4.3.2).

4.2.4 Hydrolytic Stability of FRCs

In the oral cavity, fiber-reinforced composite structures are exposed to a moist environment with changing temperatures and pH. This poses a challenge to all dental materials, including fiber-reinforced composites. Although FRCs can be seen as relatively corrosion resistant, the polymer matrix, glass fibers, and interface between them can degrade in an aqueous-aggressive medium, such as the oral cavity. Water sorption is known to decrease the mechanical properties of FRC due to swelling and plasticization of the matrix polymer and by the fiber/matrix interface hydrolytic degradation (Jancar and Dibenedetto 1993). Strength and modulus of elasticity of an FRC made of glass fibers and a semi-IPN polymer matrix decreased by approximately 15 % as a result of 30-day water storage (Valittu 2000). A more pronounced effect is seen with high water-absorbing polymers. As an example, high water sorption of polyamide matrix caused a reduction of over 50 % in the strength of the composite (Lastumäki et al. 2001). The reduction in flexural properties produced by short-time storage (e.g. 1 month) is reversible. Dehydration of the FRC will return the material's original flexural qualities (Lassila et al. 2002). In a longer aging, most of the reduction in strength and stiffness will take place in the first months' time reaching thereafter a slow and steady level, resulting in approximately 20–25 % decrease in overall flexural properties in the long term (e.g., 10 years) (Vallittu 2007).

A well-polymerized and high-quality FRC exhibits very little permanent changes of properties due to water sorption. Diffusion of water, acids, and bases is slow through the polymer matrix. FRC restorations are mostly fabricated with a multiphasic design, where a veneering composite protects the fiber-rich substructure. If, however, water or saliva comes into contact directly with the fibers, the process of degradation is sped up. Fibers may be exposed during finishing a restoration or through cracks in the composite. The polysiloxane network, which binds the fibers to the matrix polymer, is prone to hydrolysis. When exposed, it constitutes a weak boundary layer and together with a capillary effect promotes hydrolytic degradation and reduction of FRC mechanical properties.

Mechanical strength of root canal posts is found to decrease approximately 10–20 % as a result of thermocycling. Some reports of greater reduction, 40–65 % in mechanical properties, have also been published (Torbjörner et al. 1996; Lassila et al. 2004). The large discrepancy can be attributed in part to differences in testing methods. Another important factor is the variation in the quality of the FRC materials tested. Void spaces within prefabricated FRC posts promote water absorption and may influence the strength reduction (Lassila et al. 2004). Oxygen in the void spaces inhibits free-radical polymerization in the polymer surface close to the void and causes increased penetration of water (Vallittu 1997a). An example of dense FRC and a FRC with void spaces in the matrix can be seen in Fig. 4.2.

The fibers themselves are also susceptible to corrosive degradation in an aqueous environment (Ehrenstein et al. 1990). The chemical composition of glass fiber surface influences its corrosion resistance (Vallittu 1998b). High calcium-containing glasses are more susceptible to acid corrosion. The fiber surface chemical composition can be altered into more acid resistant, for example, by adding boron oxide. These alkali ions, calcium and boron oxide, are however known to leach out of glass fibers in a wet environment causing fiber surface degradation (Vallittu 2014).

4.3 Applications of FRCs in the Restoration of RCT Teeth

4.3.1 Unidirectional FRCs

A root canal post is a common application of unidirectional fiber-reinforced composites in dentistry. The use of FRC root canal posts to anchor cores and crowns to the root has rapidly increased during the last decades (Qualthrough et al. 2003; Mannocci et al. 2005). Unidirectional FRC can be used both as prefabricated fully polymerized solid posts and individually formed in situ polymerized posts.

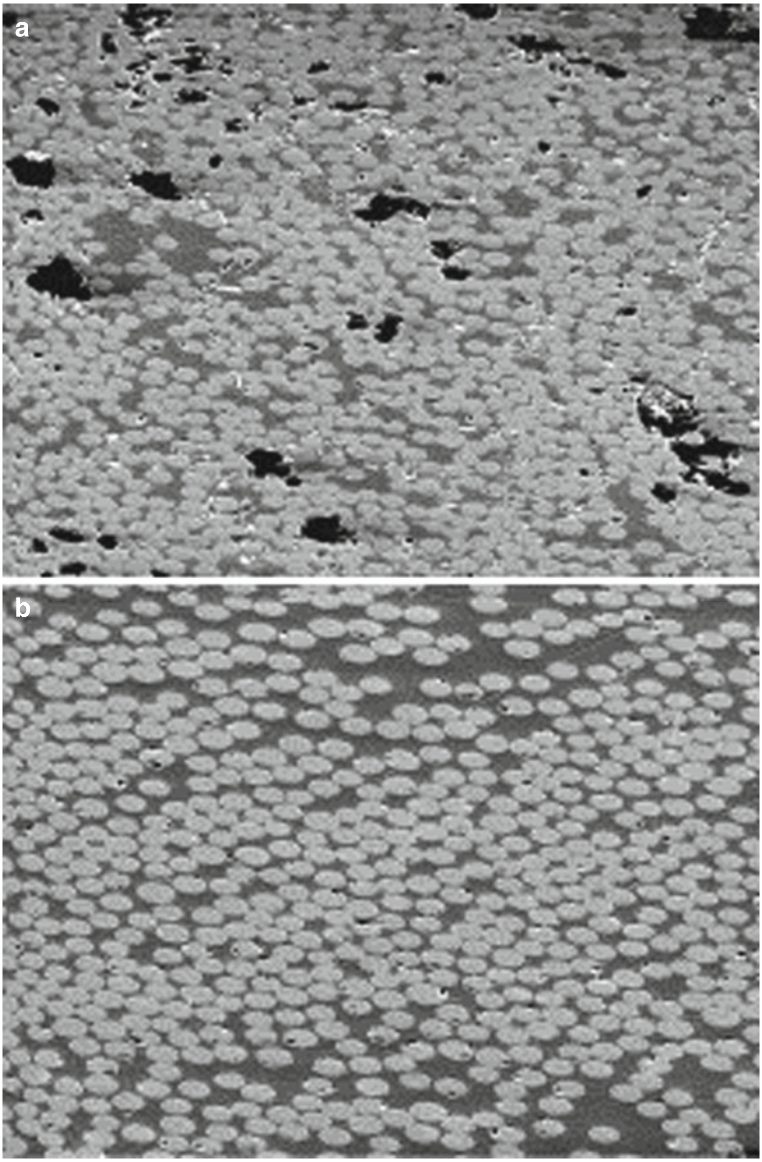

Fig. 4.2 A scanning electron micrograph showing a cross section of two different FRC root canal posts: void spaces in the polymer matrix (**a**) and a dense polymer matrix with good impregnation of fibers (**b**) (Reprinted with permission from Elsevier, Rightslink®, license no 3580140154695)

Since the first prefabricated carbon/graphite FRC post (Composipost, C-Post) in the 1990s, different glass and quartz fibers have gradually taken over the clinical field of prefabricated FRC posts (Dallari et al. 2006; Schmitter et al. 2007). The first clinical reports of carbon FRC posts reported good survival (Ferrari et al. 2000; Hedlund et al. 2003). Later, studies with longer follow-up periods have revealed

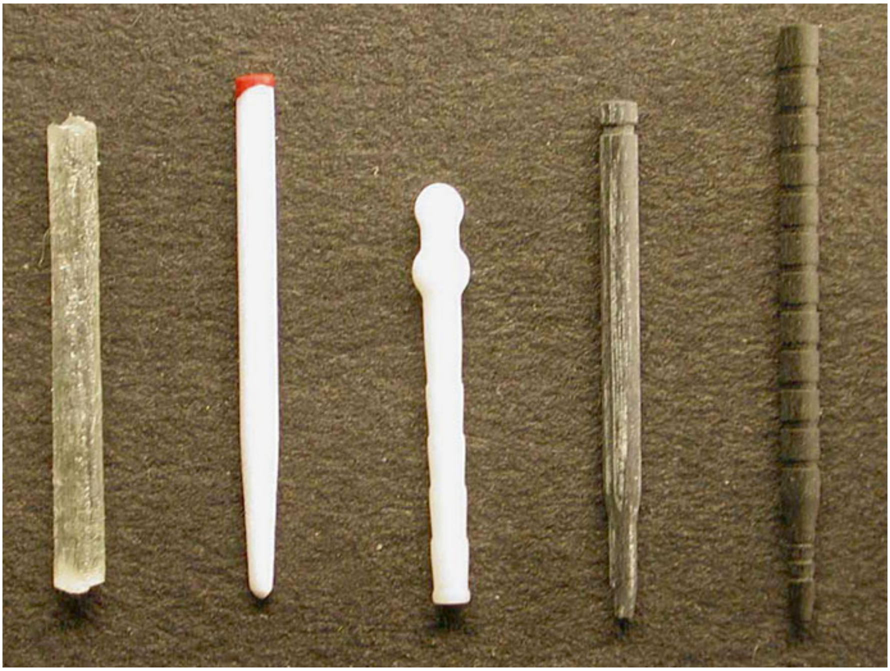

Fig. 4.3 A photograph of different types of FRC posts. From the left: everStick post, SnowPost, ParaPost Fiber White, C-Post, and C-post serrated

also some unfavorable results (Segerström et al. 2006). Higher cosmetic demands and requirements for advanced flexural behavior opted for increased development of glass FRC posts. They were also found to perform adequately in relatively short-time clinical follow-up studies (Grandini et al. 2005). Regardless of several clinical studies reporting on the performance of prefabricated FRC posts during the last 15 years, there are, however, still very few good clinical randomized clinical trials studies with longer follow-up period.

4.3.1.1 Prefabricated FRC Posts

Prefabricated FRC posts consist of a high volume percentage of continuous unidirectional reinforcing fibers in a finally polymerized polymer matrix, thus forming a solid post with a predetermined diameter. The fibers used in prefabricated FRC posts are carbon/graphite or glass (E-glass, S-glass, quartz/silica) fibers, and the matrix is usually an epoxy polymer or a mixture of epoxy and dimethacrylate resins with a high degree of conversion and a highly cross-linked structure (Fig. 4.3). The fibers contribute stiffness and strength to the usually elastic matrix. The fiber quantity in prefabricated FRC posts varies from 40 to 65 vol% (Torbjörner and Fransson 2004; Zicari et al. 2013) according to the manufacturer.

There are many suggested advantages in using prefabricated FRC posts, compared to conventional metallic posts. One of the most important benefits of glass

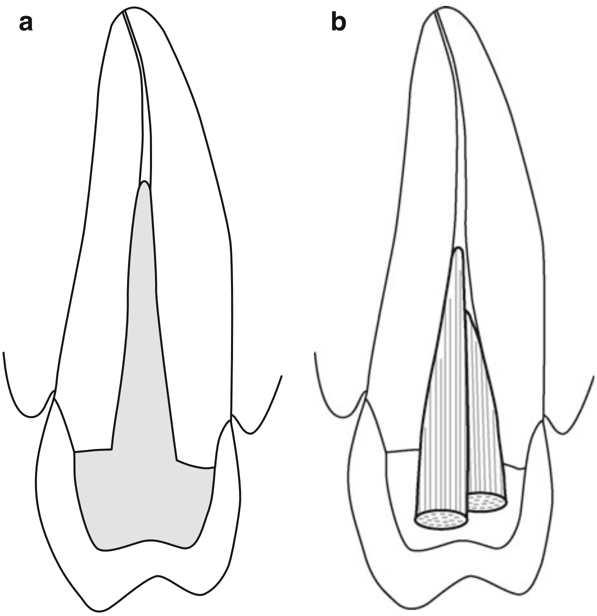

Fig. 4.4 Illustration of the restorative principle in individually formed FRC posts. Metallic custom-cast dowels and cores are traditionally made with gradual apico-coronal increase in thickness, often according to the canal anatomy (**a**). Currently, a similar structure can be made using modern fiber-reinforced composites directly in the mouth (**b**)

FRC is the suitable elastic modulus, which should result in fewer root fractures and fewer unfavorable failures (Fokkinga et al. 2004). Additional advantages of prefabricated FRC posts are the easiness of buildup and removal in situ and good esthetics, especially with the prefabricated glass FRC posts.

The advantages of glass FRC posts have been demonstrated in several studies (please refer to Chap. 6). Despite many favorable properties of prefabricated FRC posts, there are also shortcomings. The predetermined shape of a prefabricated FRC post seldom follows the anatomy of the root canal. Therefore, when placing a prefabricated FRC post, a large space will be filled with resin cement coronally, and an unnecessary amount of dentin may have to be removed apically (Figs. 4.4a and 4.5a). Additionally, the coronal part of the prefabricated FRC post-core system may not be stiff enough, to resist the high stresses produced by occlusal loads at the coronal and cervical areas (Pegoretti et al. 2002). The result is a post-core system with insufficient load-bearing capacity and a restored tooth which will not be able to resist the high stresses cervically at the restoration margins. This will lead to marginal breakdown by means of adhesive failure on the tension side of the restoration and in the end secondary caries (Schmitter et al. 2011). This problem arises particularly when the restoration is lacking a ferrule effect (Fig. 4.4) (Creugers et al. 2005).

Prefabricated FRC posts are attached to the root canal dentin using adhesives and composite resin luting cements. However, their highly cross-linked polymer matrix with a high degree of conversion is nonreactive and therefore difficult to bond to resin luting cements and core materials (Kallio et al. 2001). The bond between epoxy-based matrix of certain FRC posts and composite resin luting cements and

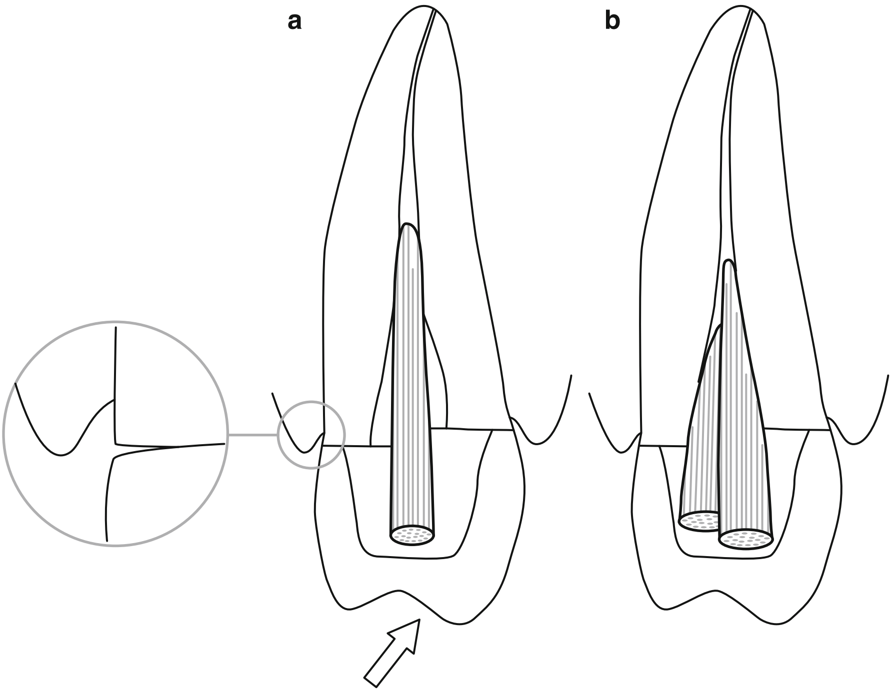

Fig. 4.5 Schematic representation of a root canal-treated tooth restored with a direct restoration lacking a ferrule effect. The use of a prefabricated FRC post with insufficient structural stiffness may result in adhesive failure on the tension side of the restoration under occlusal load (**a**). Adding fiber volume by means of an individually formed FRC post increases stiffness in the critical coronal area (**b**)

composite core material is mainly mechanical (Purton and Payne 1996; Torbjörner and Fransson 2004). To overcome the problem with adhesion, some manufacturers have added surface features, e.g., serrations (Love and Purton 1996; Al-Harbi and Nathanson 2003), to the prefabricated FRC post to increase mechanical retention of resin cements and core material. However, this has been shown to be nonbeneficial or even harmful with regard to adhesion and flexural strength of a FRC post with an anisotropic nature (Soares et al. 2012; Zicari et al. 2013). Efforts with different surface treatments, of the prefabricated FRC post surface, both mechanical and chemical, have been made to improve the bond (Mannocci et al. 1999a, b; Lastumäki et al. 2002; Kallio et al. 2003; Sahafi et al. 2003). These methods include air-particle abrasion, silanization, and resin impregnation.

4.3.1.2 Individually Formed FRC Posts

Attempts to eliminate the disadvantages of prefabricated FRC posts have given rise to new alternatives on how to restore RCT teeth with a post in an optimal way. The concept of developing an individually formed FRC post system has been evaluated with different materials in different research groups. In one study, cold-gas

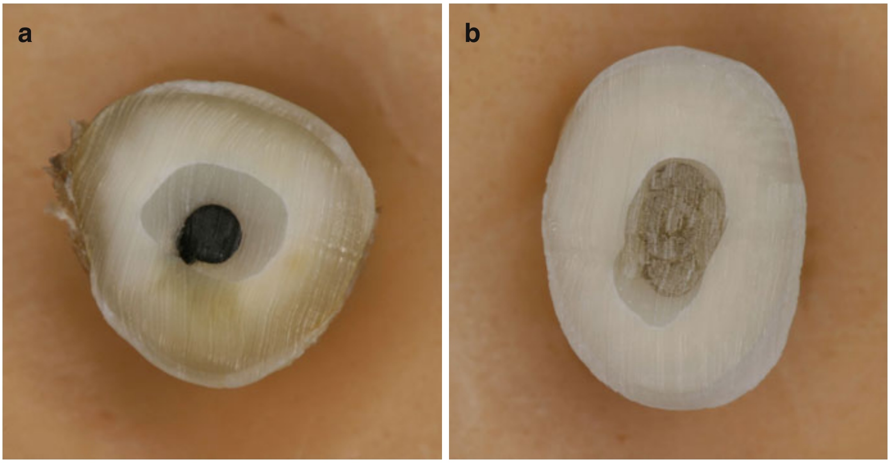

Fig. 4.6 Root canal-treated premolar teeth are restored with a prefabricated carbon/graphite fiber post (**a**) and an individually formed glass fiber post (**b**). Teeth were cut cross-sectional at gingival margin level. In a coronally flared root canal, the canal space is filled, and the tooth is reinforced more efficiently using the individual post technique

plasma-treated polyethylene woven fibers were used for this kind of concept (Terry et al. 2001). Greater resistance under loading and more favorable fractures were reported with individual customized FRC posts compared to prefabricated FRC posts (Corsalini et al. 2007). In one case report, superior fit to the root canal was obtained with a translucent fiber post covered with a layer of light-curing resin, a so-called anatomic post (Grandini et al. 2003).

Significantly higher bond strengths and fatigue resistance have been reported with individually formed glass FRC posts compared to prefabricated posts (Qualthrough and Mannocci 2003; Lassila et al. 2004; Le Bell et al. 2004, 2005; Bitter et al. 2007). These individually formed FRC posts with a semi-IPN polymer matrix are made from nonpolymerized fiber-resin prepregs, consisting of glass fibers and light-curing resin matrix (Fig. 4.3). The purpose of the individual or custom-made FRC post is to fill the entire space of the root canal in cross section with the FRC material, following the anatomical form and using minimally invasive preparation (Fig. 4.6.b). This way, more reinforcing fibers may be placed in the cervical parts of the canal where high tensile stresses occur, resulting in increased resistance (Bitter et al. 2007; Le Bell-Rönnlöf et al. 2011). The increased fiber quantity in the coronal part of the root canal increases the load-bearing capacity of the post system. A FRC post formed with this technique resembles the design of a traditional cast post and core. With gradual apico-coronal increase in thickness, following the anatomy of a modern flared canal preparation, more dentin can be saved in a structurally compromised tooth (Fig. 4.6.).

Additional benefits of the individual technique arise from bonding properties. With the individually formed FRC post, which consists of a semi-IPN polymer matrix between the fibers, the problems concerning the adhesion between post and cement are minimized. In a chair-side technique, the oxygen inhibition layer also acts as an adhesion promoter. When resins or resin based composites, such as an individually formed root canal post, are polymerized in the presence of air, a non-polymerized surface layer is formed, known as the oxygen inhibition layer (Vallittu 1997b). Resin cements can adhere to this layer and form a durable bond. The bonding of the individually formed FRC post to resin cements has been reported to be good (Le Bell et al. 2004, 2005; Mannocci et al. 2005; Bitter et al. 2007). When post dimensions closely follow the dimensions of the canal orifice, the cement thickness can be reduced (Fig. 4.5). This in part lowers the polymerization contraction stress in the adhesive layers between the post and the surrounding dentin.

The biomechanics of the tooth is better simulated by placing the fibers closer to the dentinal wall, where the highest stresses occur (Guzy and Nicholls 1979; Torbjörner 2000; Hatta et al. 2011). When the outer ferrule of the restoration is lacking, adhesive failure and marginal leakage, especially on the tension side of the tooth, are a common failure type seen in teeth restored with prefabricated FRC posts (Schmitter et al. 2011). The individual FRC post approach aims to diminish the adhesive failures of the restoration by providing increased structural stiffness and resistance in the critical cervical area (Fig. 4.4). Moreover, a tooth restored with a short and thick individual FRC post has been reported to sustain higher loads than a tooth restored with a thin and long individual FRC post (Hatta et al. 2011). This technique offers benefits also from an operative perspective. A shorter root canal preparation is less time consuming, and unnecessary hard tissue removal can be avoided.

The fundamental requirement of an adequate degree of conversion of the polymer matrix of the in situ polymerized FRC post is achieved with the individually formed FRC post material (Le Bell et al. 2003). In addition, it seems that the direct method of polymerizing the individually formed FRC post simultaneously with the resin cement in situ in the root canal may be superior to prepolymerizing, when looking at fracture load and microleakage (Hatta et al. 2011; Makarewicz et al. 2013).

4.3.2 Short Discontinuous FRCs in Restoring RCT Teeth

Fibers can also be used as reinforcements of restorative composites, and a number of researchers have focused on this topic (Krause et al. 1999; Petersen 2005). Requirements for FRCs in this field of application are specific, since the restorative material must be applied directly into a tooth preparation. Some attempts to reinforce restorative composites with fibers have failed due to insufficient fiber length. Using fibers as reinforcement throughout the material has failed due to poor polishability of the restoration surface. For the filling material to maintain its applicability, the fibers must be short and discontinuous. Yet, the fiber length should remain above the critical threshold value, in order for the fibers to provide substantial improvement in mechanical and polymerization contraction properties (Vallittu 2015). The fiber length of advanced FRCs should exceed 50 times the diameter of the fiber (critical fiber length) (Kardos 1993). When calculating the fiber aspect (l/d-) ratio of

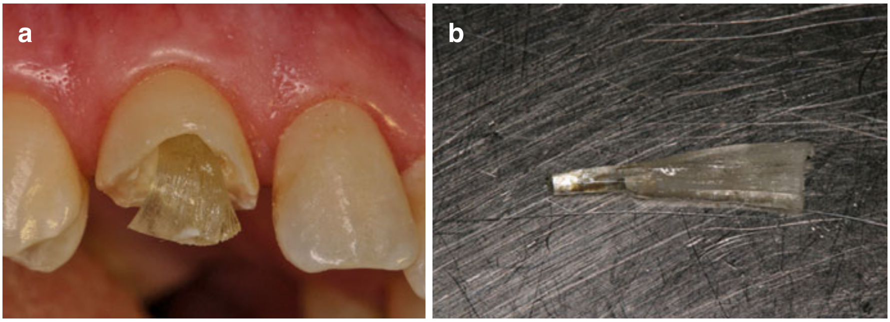

Fig. 4.7 A clinical photograph of a maxillary canine restored with an individually formed FRC root canal post (**a**). The FRC post prior to insertion showing the flared anatomical form (**b**)

contemporary dental FRCs, the critical fiber length can be determined in the range of 750–900 µm (Vallittu 1998a, b).

The current trend to use FRCs in dental fillings is as a separate base increment. Fibers in the reinforced base increment are relatively long, giving the material strength and toughness. This base layer is then covered with a conventional particulate filler composite enabling good esthetics and proper polishability. Short FRC base filling offers superior mechanical strength and fracture toughness. It also supports the PFC layer and stops crack propagation, serving as a crack prevention layer. In vitro research has shown that the use of a bilayered structure consisting of a fiber-reinforced composite substructure combined with an upper layer of conventional restorative composite increases the fracture load of a restoration (Fennis et al. 2005; Garoushi et al. 2005, 2006). Composite crowns in endodontically treated molars were also significantly reinforced with a short-fiber composite core restoration (Lammi et al. 2011).

When there is sufficient coronal dentin in RCT teeth, especially molars, a decision can be made to omit the use of a post. A short-fiber composite is well suited to restore the missing coronal dentin. Figure 4.7 illustrates the principle of using short-fiber composite to restore a moderately damaged root canal-treated molar. Short FRC adheres well to cavity walls and the overlaying composite, transferring occlusal loads evenly to the tooth. Light transmission through fibers and resulting increased polymerization depth allows for a simplified bulk-filling technique. Packing the material into the cavity forces the randomly oriented fibers perpendicular to the axial cavity walls. As discussed earlier, the polymerization contraction of an FRC is reduced in the direction of the long axis of the fibers (Tezvergil et al. 2006). The optimal fiber length for a controlled polymerization contraction has been shown to be 1–3 mm (Garoushi et al. 2007). The fiber-rich layer of the restoration also influences the crack propagation. Teeth restored with a short-fiber composite core restoration have demonstrated a more favorable fracture behavior in vitro than teeth restored with a particulate filler

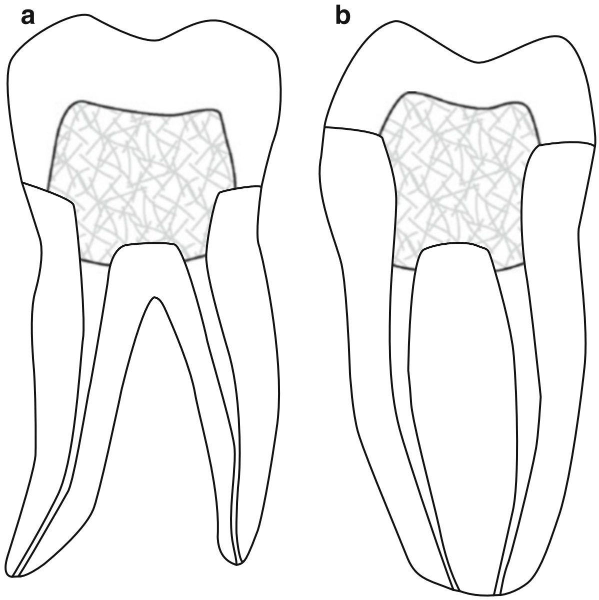

Fig. 4.8 Schematic representation of a moderately damaged root canal-treated molar restored with a short-fiber composite base filling and an onlay of particulate-reinforced composite, lateral (**a**) and mesial (**b**) view

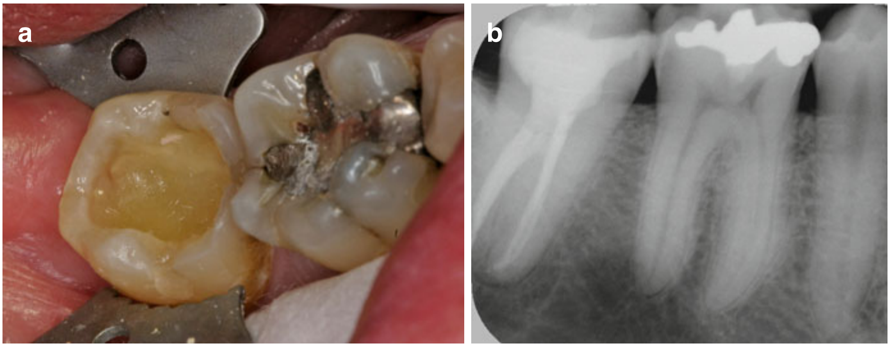

Fig. 4.9 A clinical photograph (**a**) and radiograph (**b**) of a root canal-treated molar restored using a short-fiber composite base filling

composite only (Lammi et al. 2011). Some preliminary clinical data exists of the use of short FRC in endodontically treated teeth. In a study reporting 1-year clinical follow-up data, the material was found to be clinically applicable and well suited in restoring large coronal defects in both vital and nonvital teeth (Garoushi et al. 2012). Longer follow-up and controlled clinical studies are required to evaluate the benefit of short FRC in the restoration of RCT teeth (Figs. 4.8 and 4.9).

Conclusion

Fiber-reinforced composites are a group of dental materials characterized by their anisotropic nature. They are relatively low-cost, tooth-colored materials that promote the use of adhesive and direct restorative techniques. FRCs offer several benefits in restoring endodontically treated teeth. Elastic modulus close to that of natural dentin, high tensile strength, and the suitability for cost-effective chairside techniques make fiber-reinforced composites well suited in the restoration of structurally compromised root canal-treated teeth. For optimal clinical performance, it is crucial that the factors influencing the behavior of these composite materials are well understood.

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Biomechanical Principles of Root Canal-Treated-Teeth Restored with Fiber-Reinforced Resin Posts

5

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Abstract

Adding a post affects the biomechanical response of root canal-treated teeth. This chapter discusses the biomechanical performance of anterior and posterior root canal-treated teeth restored with fiber-reinforced resin posts and the effects of post systems, post lengths, luting procedures, ferrule design, and coronal restorations. The chapter includes discussion of anatomic glass fiber posts for severely weakened endodontically treated teeth and adhesive endocrown restorations.

Endodontically treated teeth are structurally compromised by caries, endodontic access, and alterations in mechanical, chemical, and physical properties (Theodosopoulou and Chochlidakis 2009; Tang et al. 2010). Often they require a post to retain a coronal restoration. Compared with metal posts, fiber-reinforced resin posts have been considered a better option for root canal-treated teeth (Soares et al. 2012). The major advantage of the fiber-reinforced posts is that they have an

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elastic modulus similar to that of dentin, which results in a more even distribution of occlusal loads through the root (Santos-Filho et al. 2014a, b; Verissimo et al. 2014). The stress/strain distribution in root canal-treated teeth restored with fiber-reinforced resin posts depends on several factors. In this chapter the authors will discuss biomechanical principles of endodontically treated teeth restored with fiber-reinforced resin posts.

5.1 Effect of Mechanical Properties of Post Systems and Post-dentin Interaction on Stress/Strain Distribution in the Restored Teeth

Traditionally, cast metal post and cores and prefabricated metal posts were used in dental practice with relative success (Theodosopoulou and Chochlidakis 2009; Tang et al. 2010). However, cast metal post and cores have high elastic modulus and have been associated with high incidence of unfavorable root fractures. In response to the need for esthetic materials and mechanical properties similar to those of root dentin, nonmetal posts have been developed. Among the nonmetal posts, epoxy resin posts reinforced with carbon fibers, epoxy or methacrylate resin posts reinforced with quartz or glass fibers, zirconia posts, and polyethylene fiber-reinforced posts are used. Clinical and laboratory studies have shown that fiber-reinforced resin posts ("fiber posts") are an excellent option for the rehabilitation of endodontically treated teeth instead of metal posts (Goracci and Ferrari 2011; Soares et al. 2012).

The success of fiber posts can be largely explained by their stiffness properties. Fiber posts consist of a polymeric matrix of epoxy resin in which fibers are embedded. The combination of these components creates a stiffness behavior for fiber posts that is close to that of root dentin (elastic modulus 18 GPa) and preserves the natural flexibility of the tooth. The similar elastic modulus between fiber post and dentin also results in reduced stress concentration and restores stress distributions that are closer to the sound tooth (Fig. 5.1a, c). Cast metal post and cores have a high elastic modulus compared with root dentin, creating a more rigid restorative complex that causes high stress concentrations in the root (Fig. 5.1b). These high stresses have been implicated in the high incidence of vertical root fractures (Lertchirakarn et al. 2003). It was shown that low elastic modulus of glass fiber posts decreases the risk of adhesive failures due to the lower stress values at the post-cement interface (Santos et al. 2010; Goracci and Ferrari 2011). Teeth restored with glass fiber posts have lower risk of root fracture because the failure is more likely to occur between the composite core and the post. Additionally, unlike glass fiber posts, cast metal post and cores are not bonded to dentin, which contributes to areas with high stresses in the restored teeth (Fig. 5.1c).

Another factor to be considered in post selection is the amount of stress generated during post placement. Metal threaded posts produce high stress concentrations in root dentin at each thread, causing strains that may create cracks, as can be observed in the scanning electron micrograph in Fig. 5.2 (Santos Filho et al. 2013).

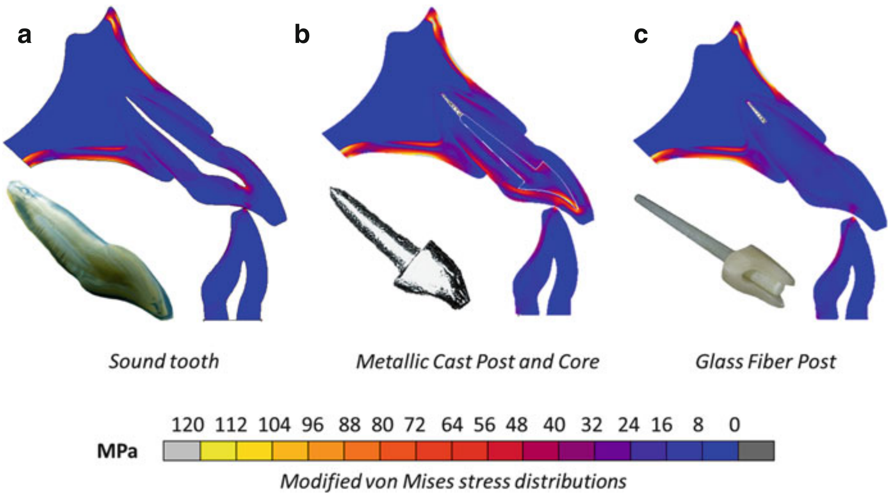

Fig. 5.1 Two-dimensional finite element stress analysis of endodontically treated teeth with different post systems. (**a**) Sound tooth; (**b**) Metallic cast post and core and (**c**) glass fiber post

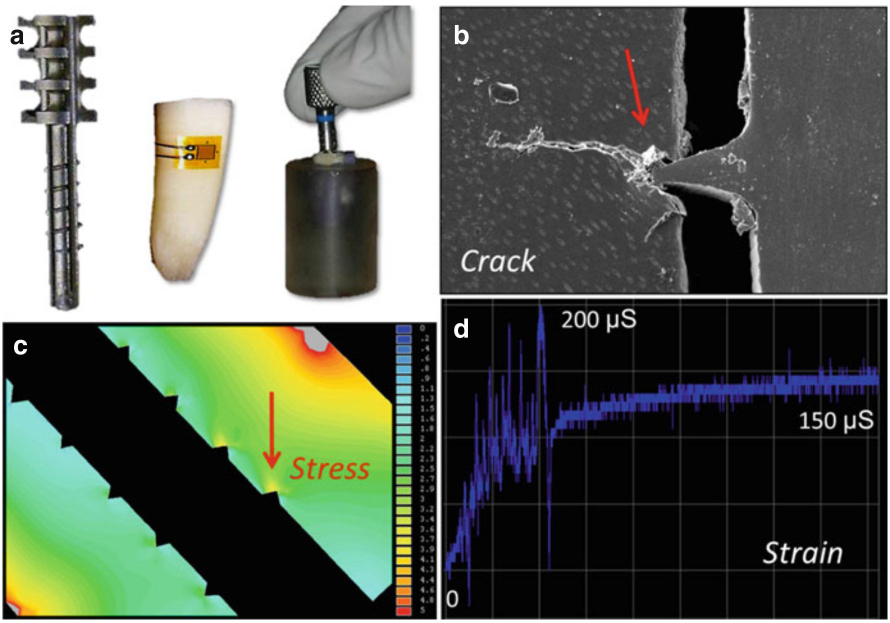

Fig. 5.2 Strain gage analysis of a metal threaded post placement (Radix-Anker). (**a**) Manual post threading procedure and induced strain acquisition; (**b**) scanning electron micrograph showing a dentin crack created by a threaded post; (**c**) Von Mises stress concentrations at the post thread; (**d**) external root strain induced by the threaded post (Figure adapted from Santos Filho et al. 2013)

5.2 Effect of Post Length on Mechanical Properties of Endodontically Treated Restored Teeth

The restoration of endodontically treated teeth can be affected by several factors, such as the amount of ferrule, post diameter and design, and post material. These factors modify the stress distribution, thus fracture resistance of these teeth. Shorter cast post and cores exhibit poor biomechanical performance and high incidence of catastrophic failures (Santos-Filho et al. 2014b). Some studies have suggested that the correct post length should be at least the length of the crown or two-thirds the length of the remaining root. However, this concept was developed for cast metal post and cores that are retained by friction. Clinically, the length of the post may be limited by root curvature or an obstruction in the root canal. Glass fiber posts have the advantage of bonding to dentin and therefore are less restricted by the required length compared to cast post and cores (Santos-Filho et al. 2008).

Finite element analysis showed that the stress distribution of endodontically treated teeth restored with glass fiber posts were not significantly influenced by the post length (Fig. 5.3) (Santos-Filho et al. 2014b). However, whenever possible, a clinician should still prepare the post space for two-thirds of the root length to increase the bonding surface, allowing for a better retention between the glass fiber post and the root canal.

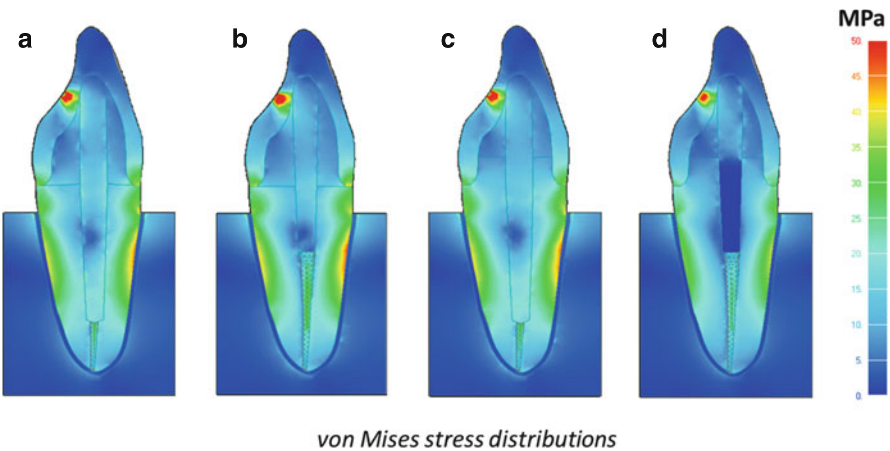

Fig. 5.3 Three-dimensional finite element stress analysis of endodontically treated teeth with different post systems and post lengths. (**a**) Without ferrule and 12 mm glass fiber post; (**b**) without ferrule and 7 mm glass fiber post; (**c**) with 2 mm ferrule and 12 mm glass fiber post; (**d**) with 2 mm ferrule and 7 mm glass fiber post

5.3 Biomechanical Performance of Fiber Posts on Anterior vs. Posterior Teeth

Anterior or posterior teeth have specific functions in the mouth, which determine their loading conditions and anatomy. Posts placed in anterior teeth (incisors and canines) were reported to be three times more likely to fail than those of posterior teeth (premolars and molars) (Naumann et al. 2005). This may be explained by the higher horizontal force components on anterior teeth compared with posterior teeth (Naumann et al. 2005). Glass fiber posts have performed well for all teeth, although the fracture resistance is lower for incisors and premolars when compared with canines and molars (Castro et al. 2012). More catastrophic failures were found when cast metal post and cores were used. Glass fiber posts were effective for restoring of endodontically treated molars regardless of the remaining tooth structure (Santana et al. 2011).

5.4 Restoring Weakened Endodontically Treated Teeth with Anatomic Fiber Post

Endodontically treated teeth can be significantly weakened with canals that are flared by the progression of caries in combination with endodontic access and/or overpreparation (Silva et al. 2011). Restoration of such severely weakened teeth is a challenge because they are more prone to fracture and fatigue. Fiber posts with suitable shapes that fit flared canals are not readily available. Cast metal post and cores have been used, but the morphology of flared canals results in very wide, tapered, and non-retentive posts. Moreover, the use of metals with high elastic modulus can cause high stress concentrations as discussed above (Fig. 5.4). A standard geometry glass fiber post leaves excess space within the flared root canal to be filled with a bulk of luting cement. This results in a potentially weak area, which may compromise the long-term prognosis (Silva et al. 2011).

A simple alternative method is to reline glass fiber posts with composite resin (Fig. 5.4). Post surface can be treated with 24 % hydrogen peroxide for 3 min followed by a silane and adhesive system to allow bonding (de Sousa Menezes et al. 2011). Clinicians can also use conventional hydrogen peroxide used for in-office dental whitening (35 %); however, the surface treatment time is reduced to 1 min (Menezes et al. 2014). After the post surface treatment, the root canal walls should be isolated with water-soluble gel. Composite resin is then added to create an anatomic post to match the morphology of the flared canal. A substantial portion of uncured composite material is placed around the glass fiber post and inserted inside the root canal. Prior to curing, the relined post must be removed and reinserted in the root canal to ensure good adaptation without locking. With the relined post

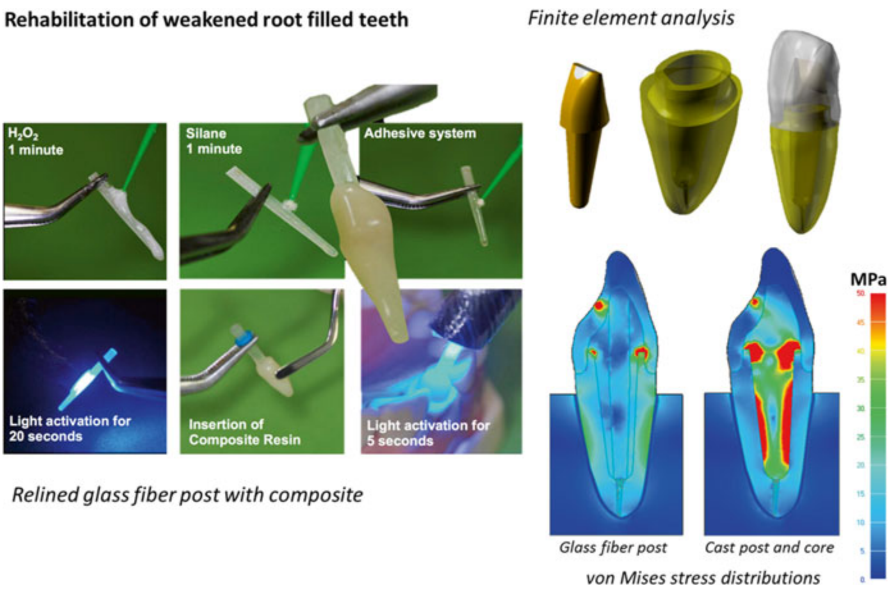

Fig. 5.4 Rehabilitation of weakened endodontically treated teeth with a glass fiber post relined with composite resin before cementation

reinserted, the composite is tack cured for 5 s. The complete composite photoactivation (20 s) is performed outside of the root canal. After the relining procedure, the composite surface is etched with 37 % phosphoric acid and rinsed with air-water spray for 20 s. Subsequently, an adhesive system is applied and light cured. The anatomical glass fiber post should be reinserted into the canal and satisfactory adaptation ensured before proceeding with the luting procedure.

This anatomic post reduces the volume of luting cement and adapts better to the canal wall. Because composite resin has an elastic modulus close to that of dentin, it creates a homogeneous stress distribution between the anatomical composite post and dentin surface that is similar to a sound tooth (Santos et al. 2010; Silva et al. 2011; Santos-Filho et al. 2014a). Anatomical posts relined with composite resin resulted in the highest fracture resistance compared with other methods (Santos et al. 2010).

5.5 Effect of Luting Procedures

Luting is an important step for the successful retention of fiber-reinforced posts. The type of resin cement and adhesive system, as well as the endodontic sealers that are used, determines the luting procedures.

There is a wide range of luting products available. Resin cements have potentially good mechanical and adhesive properties, but they can be complex and highly sensitive to the luting technique. Resin cements used for the luting procedure can be classified according to polymerization reaction: auto(chemical) activation, photoactivation, or dual activation (auto- and photoactivation). The literature shows that resin cements with dual activation generally attain higher bond strengths to root dentin.

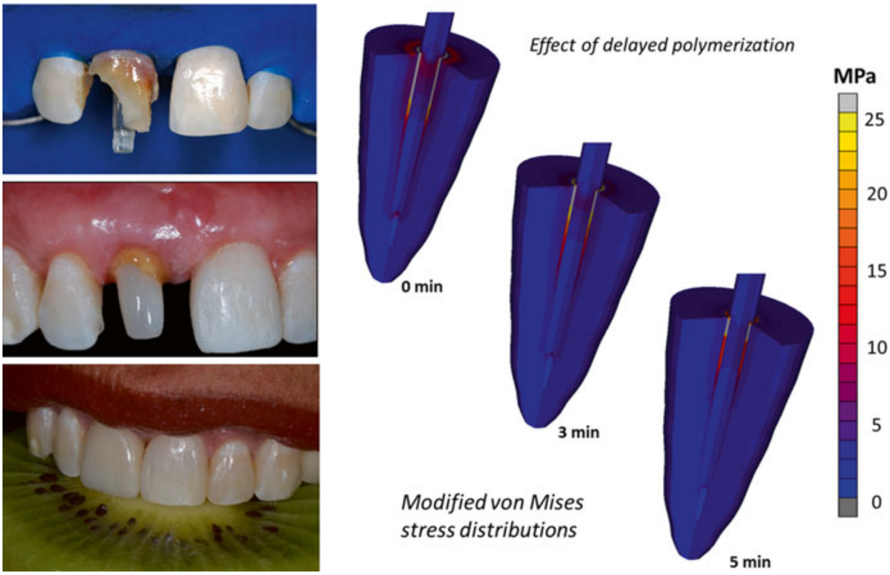

Fig. 5.5 Luting procedure and the effect of immediate, 3- and 5-min delayed polymerization on resin cement shrinkage stress (Figure adapted from Pereira et al. 2015)

Conventional resin cements are sensitive to root canal depths because a lower density of dentinal tubules in the apical region reduces the bond strength to root dentin. A literature review and meta-analysis of in vitro studies suggest that the use of self-adhesive resin cement might improve the retention of glass fiber posts in root canals (Sarkis-Onofre et al. 2014). Self-adhesive resin cements do not require a separate adhesive. The use of a self-adhesive cement involves chemical bonding of the cement with hydroxyapatite in root dentin and promotes mild dentin demineralization and infiltration. Therefore, these cements have chemical reaction and micro-retention. Recent studies have shown that the bond strengths of these cements are higher than those of conventional resin cements, being less susceptible to luting depth (Ferracane et al. 2011).

Luting procedures determine the success of fiber posts and if restorations are retained. Factors affecting the luting procedures are discussed elsewhere in this book. A unique technique highlighted in this chapter is a procedure in which a time delay is applied between the cement mixing and photoactivation. Such delay improves the bonding of dual-cured resin cement to dentin without diminishing the mechanical properties (Khoroushi et al. 2012; Faria-e-Silva et al. 2014). A rapid increase in cement viscosity by immediate light irradiation can hinder the reaction of acidic monomers with dental tissues and weaken the bond. Additionally, a delayed setting of dual-cured resin cement may reduce polymerization shrinkage stress. Regardless of resin cement type, 5-min delayed photoactivation improved the mechanical properties of resin cement and decreased stresses generated by post-gel shrinkage (Fig. 5.5) (Faria-e-Silva et al. 2014; Pereira et al. 2015).

Fiber posts allow coronal reconstruction to be performed in one session. However, the type of endodontic sealer may influence the bond strength between the root dentin and post. Clinicians may have to be careful with eugenol-based sealers if the luting procedure is performed following the endodontic treatment. As any phenolic compound, eugenol inhibits the polymerization of resin-based material. The hydroxyl group in eugenol reacts with free radicals formed during resin polymerization, thereby reducing the degree of conversion of these materials and resulting in reduced bond strengths. When calcium hydroxide-based sealers were used, bond strengths of fiber-reinforced posts were not lower if the luting procedure was performed immediately or 7 days after root filling (Menezes et al. 2008). Endodontic sealers based on calcium hydroxide can thus be used for the luting procedure immediately after the endodontic treatment. Nevertheless, this topic remains controversial as mentioned in Chaps. 6, 7, and 9.

5.6 Effect of Ferrule Design on Biomechanical Behavior of Endodontically Treated Restored Teeth

The height of the remaining coronal dentin structure, known as ferrule (please see Chap. 1), offers support to the remaining coronal tooth structure against occlusal loading and lateral forces exerted during post insertion. The presence of ferrule generally improves the stress distribution in the root and increases the fracture resistance of endodontically treated teeth regardless of the type of post systems (Fig. 5.6). However, post systems do affect the mode of failure of endodontically treated teeth with ferrules. Understanding mode of failure is important to avoid catastrophic types of fractures. Cast metal post and cores that do not have a ferrule have been associated with a high incidence of unfavorable failures. Stress analysis has shown that cast post and cores create high stress concentrations inside the root canal that could create conditions that initiate vertical fracture (Sterzenbach et al. 2012). Furthermore, such high stress concentrations can lead to microgaps at the cement-dentin interface or cement-post interface, resulting in bacterial colonization and periapical lesions (Sterzenbach et al. 2012).

Using in vitro tests and finite element analysis, Veríssimo et al. (2014) showed that a 2 mm circumferential ferrule helped create the best stress distributions for endodontically treated teeth. A literature review confirmed that a circumferential coronal structure extending 1.5–2 mm from the margin of the crown has a better prognosis (Juloski et al. 2012). If the clinical situation does not allow a circumferential ferrule, an incomplete ferrule is still considered a better option than no ferrule. Conservation of tooth structure is thus as important as choosing suitable restorative materials for creating the best biomechanical behavior.

5.7 Effect of Coronal Restoration on Biomechanical Behavior of Endodontically Treated Teeth Restored with Fiber Posts

The last step in the rehabilitation of endodontically treated teeth is the coronal restoration. The choice of restoration is mainly influenced by the amount of remaining tooth structure. Options range from composite resin restorations to full crowns fabricated with resin composites, ceramics, or metals.

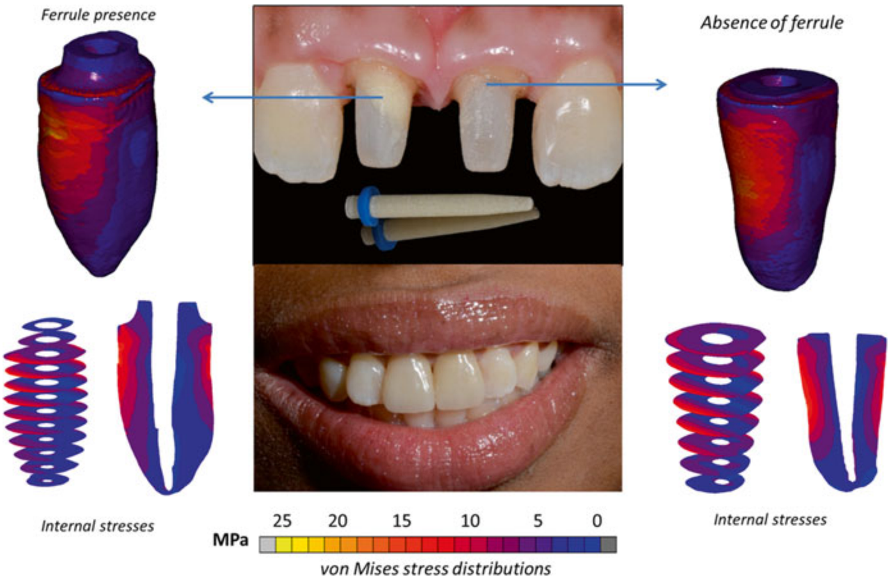

Fig. 5.6 Three-dimensional finite element analysis of endodontically treated teeth restored with glass fiber posts with or without ferrule (Figures from PhD Thesis of Andrea D. Valdivia, Federal University of Uberlândia)

Endodontically treated teeth with large class III preparations restored with direct composite resin veneers without posts showed a higher incidence of root fractures than teeth restored with the same technique but with glass fiber posts (Valdivia et al. 2012). An all-ceramic crown provides a protective effect for the lower elastic modulus core materials and glass fiber posts because a crown with high elastic modulus spreads the high loads over a larger area. As a result, an all-ceramic crown may fail before the core, post, or tooth structure (da Silva et al. 2010).

5.8 Beyond Fiber Post Restorations: Monolithic Adhesive Endocrown Restorations for Endodontically Treated Teeth

Endodontically treated teeth are usually restored with a core buildup, with or without post and crown. With the advent of adhesive dentistry, the need for using post and core has become less evident (Biacchi et al. 2013). Bonding and/or luting materials are required for adhering post, core, and crown together. However, each adhesive interface risks bond failure and thus become a critical factor in the restorative prognosis. For certain cases of endodontically treated teeth, endocrowns may be a good alternative restoration. An endocrown is a monolithic adhesive restoration, containing a coronal restoration integrated with an apical projection that fills the pulp chamber space and part of the root canal (Fig. 5.7). The projection toward the pulp chamber and coronal canal provides the retention (Bindl and Mormann 1999;

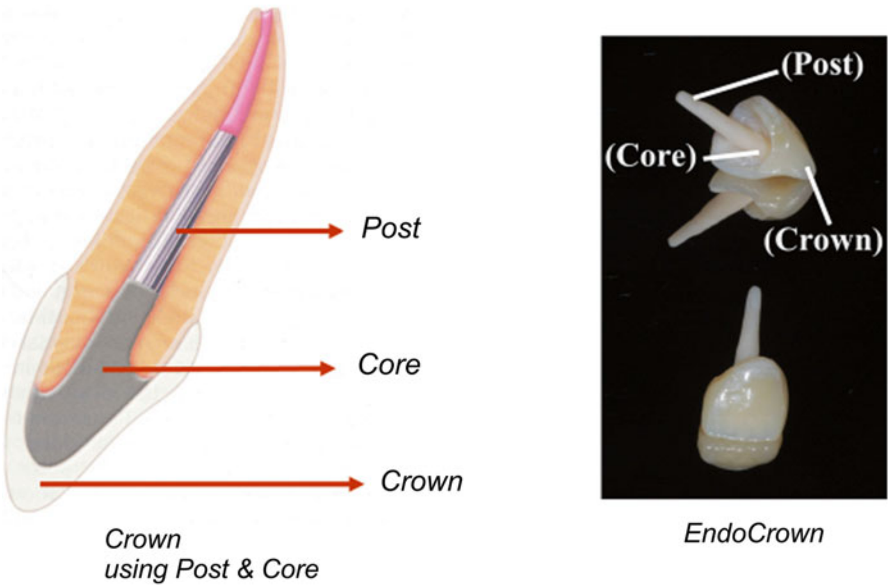

Fig. 5.7 Comparison of conventional crown with post and core versus endocrown

Gohring and Peters 2003). By eliminating or reducing the number of adhesive interfaces, the endocrown restoration is less susceptible to adverse effects of bond degradation. The clinical procedure to fabricate endocrown restorations is also less complicated, more practical, and easier to perform than a post and core with crown (Dejak and Mlotkowski 2013).

The overall failure probability for endocrowns has been found to be similar to traditional crowns. Stress values in dentin and luting cement for endocrown restorations were lower than those with traditional crowns. Finite element analyses showed that teeth restored with endocrowns were potentially more resistant to failure than those restored with fiber posts (Dejak and Mlotkowski 2013). Weibull analysis suggests that the individual failure probability of dentin and luting cement decreased more with endocrowns than with traditional crowns. Clinical studies have confirmed the functional longevity of endocrowns (Biacchi et al. 2013).

Endocrowns offer advantages for conservative restoration of endodontically treated teeth by restoring function, esthetics, and maintaining the biomechanical integrity of the compromised structure of endodontically treated teeth with competitive cost and less clinical time (Figs. 5.8 and 5.9) (Lin et al. 2010). Endocrowns are suitable for restoring teeth with extensive coronal destruction because they use the

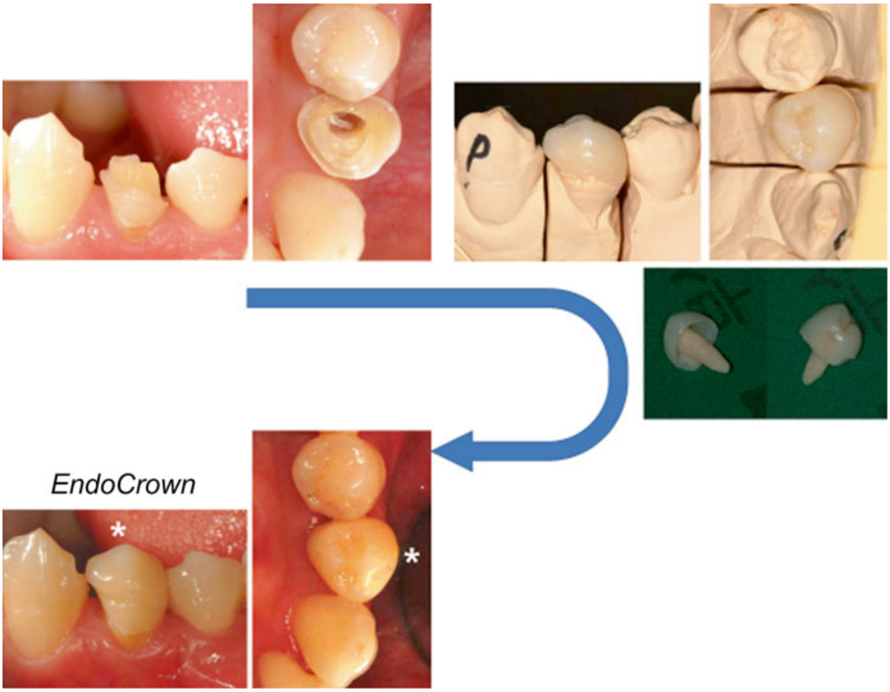

Fig. 5.8 Clinical case of endocrown (*) on mandibular first premolar using Tescera (Bisco Dental Products)

entire extension of the pulp chamber for retention instead of intraradicular posts (Pissis 1995; Zarow et al. 2009). The simple and efficient concept of endocrowns is compatible with the philosophy of biointegrated restorations. This type of reconstruction is still uncommon, but should be more widely used (Biacchi and Basting 2012; Fages and Bennasar 2013).

Fig. 5.9 Clinical case of endocrown on maxillary central incisors with correction of the tooth axis

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Fiber-Reinforced Resin Posts (Fiber Posts)

6

Jorge Perdigão

Abstract

The restoration of endodontically treated teeth has been subject of controversy over many years. It was believed that the exclusive function of a post was to provide retention for the coronal restoration. More recent evidence suggests that fiber-reinforced resin posts (or fiber posts) may actually strengthen the root when luted with an adhesive technique.

Fiber posts have an elastic modulus similar to that of dentin, which may make them mechanically compatible with root canal dentin. Clinical studies have reported lower incidence of catastrophic fractures with fiber posts compared to more rigid posts. As clinical success depends on both the quality of the root canal treatment and that of the coronal restoration, the challenge faced by clinicians is to achieve a tight seal between the root canal walls and the fiber post, while retaining the post securely to the root canal walls.

This chapter describes the types of prefabricated posts, advantages and disadvantages of each type, and frequent myths associated with the use of posts in the root canal, besides clinically relevant considerations including a review of some clinical studies.

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6.1 Introduction

The concept of using prosthetic radicular extensions to secure coronal restorations has been used in dentistry for many years. In 1871 Drs. Harris and Austen wrote "The artificial crown may be secured to the root by means of a pivot made of wood or metal; when the latter is employed, gold or platina is to be preferred, inasmuch as silver or any baser metal is liable to be oxidized by the fluids of the mouth." The objective of an intra-radicular dowel or post is to protect the weakened endodontically treated tooth from root fracture that may occur as a result of the concentration of internal stresses (Gutmann 1992).

Black (1895) reported that the dentin of human pulpless teeth has less crushing strength than that of normal teeth. There is 9 % less moisture in the calcified tissues of pulpless teeth than in the calcified tissues of vital teeth (Helfer et al. 1972). Jameson et al. (1993) reported that strain at fracture and fracture energy were significantly greater for hydrated and rehydrated dentin than for dehydrated dentin. The effect of dehydration on the dentinal tubules has been associated with increased weakness and brittleness in pulpless teeth (Huang et al. 1992).

The loss of moisture is more intense in anterior than in posterior teeth (Helfer et al. 1972), which may explain the higher incidence of failure in anterior than in posterior endodontically treated teeth (Mancebo et al. 2010). As seen in Chap. 2, as a result of the lower moisture contents in dentin of pulpless teeth, it is believed that endodontically treated teeth are more susceptible to fracture than they were before endodontic therapy. However, the general perception is that removal of root dentin is the major factor responsible for weakening teeth (Schwartz and Robbins 2004). It is currently understood that the loss of structural integrity associated with the access preparation is the major cause of occurrence of fractures in endodontically treated teeth compared with vital teeth (Schwartz and Robbins 2004). The preparation of a post space results in weakened endodontically treated teeth compared with teeth in which only the endodontic access is open, but no post space is prepared (Trope et al. 1985). There is a direct relationship between the amount of tooth structure that is lost in cavity preparation and the deformation that occurs under load (Tidmarsh 1976). As discussed in Chap. 2, root canal access preparations remove a substantial part of the coronal dentin, making the tooth susceptible to fracture under relatively low load. *The fracture resistance of the endodontically treated tooth decreases with a decrease in residual dentin and the strength of the restored tooth is directly related to the remaining bulk of dentin* (Trabert et al. 1978; Mattison 1982; Sorenson and Martinoff 1984).

The changes in root dentin are also a factor that influences the behavior of restored teeth. For example, the apical area of root dentin has fewer tubules than the occlusal part (Fig. 6.1). As teeth age and more peritubular dentin is deposited within the dentinal tubules, less space exists for organic material and tissue fluid, both of which lend flexibility to living tissue. Transparent dentin, sometimes called sclerotic (Nalbandian et al. 1960; Kinney et al. 2005), forms gradually with aging, starting in the root area (Fig. 6.2). Differences in the structure and mechanical properties of normal vs. transparent dentin have been reported (Balooch et al. 2001; Kinney et al. 2005). The mineral concentration is significantly higher in transparent dentin, which results in closure of

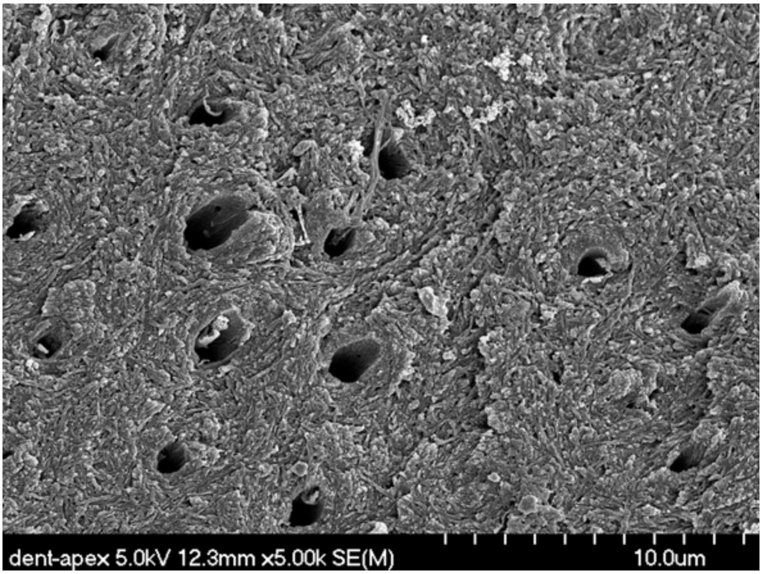

Fig. 6.1 Scanning electron micrograph depicting the apical third of a human molar. Original magnification = ×5,000

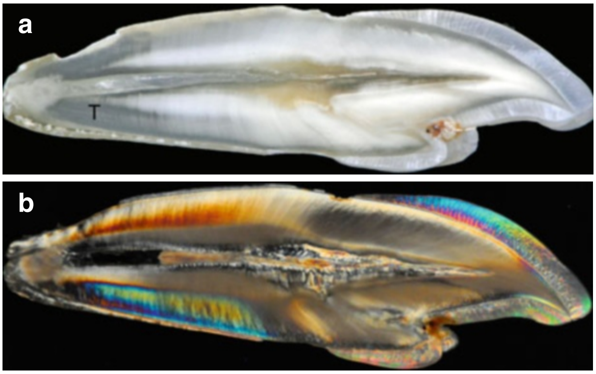

Fig. 6.2 (**a**) Longitudinal section of a mandibular canine with transparent dentin (*T*) forming on the apical third. In (**b**) the same section is shown in polarized mode

the tubule lumina (Fig. 6.3). The elastic properties are unchanged in transparent dentin. However, transparent dentin exhibits almost no yielding before failure, which is not observed in normal dentin. The fracture toughness in transparent dentin is lowered by 20 %. Some of the changes that occur in dentin with aging are displayed in Table 6.1.

6.2 General Principles for All Prefabricated Passive Posts

The ability of dentists to restore endodontically treated teeth increases the chance of patients retaining teeth that were formerly condemned to extraction. All teeth require a definitive restorative treatment after the root canal therapy is completed

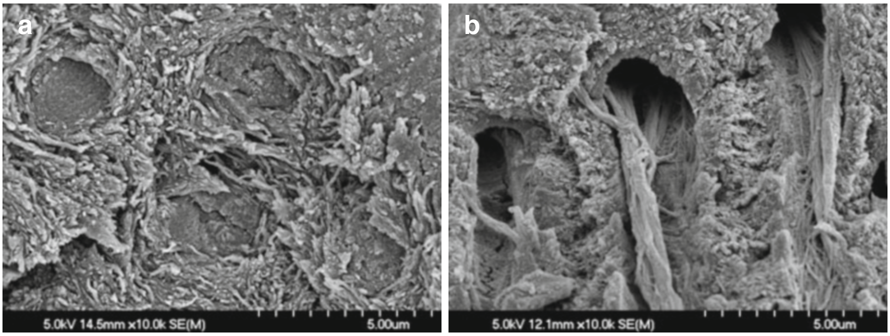

Fig. 6.3 Scanning electron micrograph depicting fractured dentin specimens. (**a**) Transparent dentin with tubules obliterated with mineral deposits; (**b**) normal root dentin showing patent tubules. Original magnification = x10,000

Table 6.1 Changes in dentin substrate with aging

The mineral concentration is higher in transparent dentin than in normal dentin
Obliteration of the dentinal tubules by increased deposition of peritubular matrix
Transparent dentin, unlike normal dentin, exhibits almost no yielding before fracture
Flexural strength and strain to fracture of dentin decreased significantly with age
Fracture toughness is lowered by roughly 20 % in transparent dentin
Aging results in an increase in the rate of damage initiation and propagation in dentin
Decrease in dentin permeability with aging
Older dentin contains less water than younger dentin
Hardness and modulus of elasticity of aged dentin are higher than those of young dentin
The density of odontoblasts and pulp fibroblasts decreases in older dentin
Transparent dentin accumulates in the apical third of the root resulting in and variations in tubule diameter and mineral deposits in the tubules
Fatigue strength of young dentin is greater than that of older dentin
Sclerotic and old dentin results in thinner hybrid layers, with short resin tags, and fewer lateral branches than normal dentin

Pashley (1996), Balooch et al. (2001), Kinney et al. (2005), Prati et al. (1999), Murray et al. (2002), Jameson et al. (1993), Arola and Reprogel (2005), Kahler et al. (2003)

and deemed successful. *Failure to adequately restore the endodontically treated tooth may cause endodontic failure* (Safavi et al. 1987).

Intra-radicular metal posts double the fracture resistance of endodontically treated teeth (Kantor and Pines 1977). A dowel was considered necessary to prevent root fracture of endodontically treated teeth long before the introduction of fiber-reinforced resin posts (or fiber posts) and zirconia posts (Randow and Glantz 1986; Goodacre and Spolnik 1994).

A few classical principles are still used currently for all types of dowels. Some of these concepts may not extrapolate directly to fiber posts due to the differences in composition, physical properties, and distinct luting techniques. *Posts are retained in the root canal either actively or passively*. Active posts engage the dentinal walls of the preparation upon insertion, whereas passive posts do not engage root dentin walls, relying instead on a luting material for retention (Smith et al. 1998). Passive posts are, therefore, less retentive than active posts. Active posts create more stresses during placement, *which may favor the vulnerability of the root structure to fracture*. In order to avoid root fracture, the use of passive tapered posts has been recommended (Gutmann 1992; Morgano 1996). When a passive post is used, its retention relies highly on the adaptation of the post to the root canal wall and the luting agent layer (Schmage et al. 2005). A cement joint value between 24 and 31 μm for the cast post, and 30 and 50 μm for the prefabricated post, may be required to minimize the failure rate of posts (Johnson and Sakumura 1978).

The longevity of restored endodontically treated teeth is affected by many factors including the post design, length, and thickness, the ferrule effect, cementation, and the amount of residual tooth substance (Lassila et al. 2004; Ferrari et al. 2012; Juloski et al. 2012). In the past clinicians and researchers have assumed that a post should be rigid (Torbjörner et al. 1996). A rigid post is capable of resisting loads without distortion. However, stresses are transferred to the less rigid component, in this case root dentin, which may result in mechanical failure (Torbjörner et al. 1996). Other factors may influence the load capability of endodontically treated teeth. The tooth morphology, the restorative techniques, and, more importantly, the amount of remaining tooth structure are fundamental variables that influence the mechanical resistance of endodontically treated teeth (Trope et al. 1985; Gutmann 1992; Sornkul and Stannard 1992; Fernandes and Dessai 2001).

A higher modulus of elasticity (greater rigidity) of the post material, besides a wider post diameter (or thickness), has been associated with increased stress values at the post-dentin interface. It has been suggested that a post should have the same modulus of elasticity (rigidity) as root dentin to distribute applied forces evenly along the length of the post (Assif et al. 1989), thus avoiding stress concentration and minimizing the risk of root fractures. This requirement seems to be fulfilled by current fiber posts, as their elastic modulus is similar to that of dentin (Zicari et al. 2013a). The elastic modulus of fiber posts is more similar to that of dentin than the elastic modulus of other types of posts (Asmussen et al. 1999).

> Fiber posts distribute stresses more uniformly along the cement–dentin interface and to the remaining tooth structure. In contrast, the moduli of elasticity of alloys used for cast posts are much higher.

6.3 Post Design

6.3.1 Post Length

As discussed in Chap. 1, Abramovitz et al. (2001) demonstrated that 3 mm of gutta-percha provided an unpredictable in vitro apical seal; therefore, at least 5 mm would be recommended (Fig. 6.4). When posts were two thirds of the root length, many of the average and short root length teeth had compromised apical seals. When the post

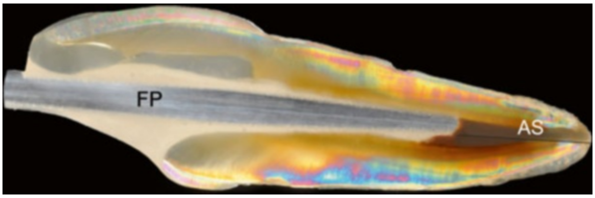

Fig. 6.4 Polarized imaged of an endodontically treated maxillary canine with a fiber post (*FP*) luted with a self-adhesive cement. The apical seal (*AS*) of gutta-percha is 5 mm long

was equal to the crown length, an adequate seal was only possible on teeth with average or long root lengths. With short-rooted teeth, even the shorter post guideline of being equal to the crown length produced a compromised apical seal.

Most principles currently applied to post length were introduced when prefabricated metal posts and cast dowels were the only options available. Sorenson and Martinoff (1984) reported 97 % success in mandibular molars if the post length equaled at least the crown length. Goodacre and Spolnik (1995) recommended a post length equal to 3/4 of root canal length. Posts with a length at least three fourths of the length of the root offered the greatest rigidity and least root deflection (bending). These posts were better than those that were one fourth or one half of the root length (Leary et al. 1987).

When the tensile force required to remove a post from extracted maxillary lateral incisors was measured, posts that were three fourths or more of the root length were 20–30 % more retentive than posts that were one half of the root length or equal in length to the crown (Johnson and Sakumura 1978). In a recent in vitro study, post spaces were prepared with a depth of 6 or 3 mm without or without maximal fit to the root canal walls (Büttel et al. 2009) in severely damaged teeth without a ferrule. Both groups (with or without maximal fit) with fiber post insertion depths of 6 mm resulted in significantly higher mean failure loads than the groups with post-space preparation of 3 mm. Reduction of the post extension above the level of bone has been associated with increased dentinal stresses near the apex of the post (Al-Omiri et al. 2011).

The fracture resistance of the endodontically treated tooth is influenced by post length.

6.3.2 Post Thickness

Classical concepts on the thickness of cast metal dowels were described by Shillingburg et al. (1982). These authors wrote "the dowel must not be made so large, however, that it will destroy precious tooth structure and the structural integrity and natural strength of the tooth." Based on the measurements of 50 permanent teeth of each type (except third molars), these authors recommended a diameter from 0.7 mm for mandibular incisors to 1.7 mm on maxillary central incisors. Additionally, dowel diameter should not be greater than one-third of the root at the cementum–enamel junction.

The removal of internal tooth structure during endodontic therapy is accompanied by a proportional increase in stress, specifically at the cervical area (Hunter et al. 1989). While fit of tapered posts in root canals, also called form congruence, has been deemed a relevant factor for prefabricated titanium post systems (Schmage et al. 2005), *the retention of fiber posts does not seem to be affected by post fit* (Perdigão et al. 2007; Büttel et al. 2009). While minimal root canal enlargement for a post does not substantially weaken a tooth (Hunter et al. 1989), *a wider post diameter has been associated with increased stress* (Al-Omiri et al. 2011).

An increase in root length increases the resistance to fracture (Trabert et al. 1978); overpreparation of the post space to insert thicker metal posts results in no tooth reinforcement, but decreases the resistance to fracture (Trabert et al. 1978; Mattison 1982). The fracture strength of endodontically treated teeth is not increased when a metal post is luted into the root canal (Trope et al. 1985; Goodacre and Spolnik 1994). And there is no significant reinforcement achieved by cementing a metal post into an endodontically treated tooth that was intact except for the access opening (Guzy and Nicholls 1979).

The maximum fracture load for fiber posts increases with their diameter (Zicari et al. 2013a), but flexural strength and flexural modulus decrease with an increase in post diameter. Whereas fiber posts with a small diameter do not result in excessive removal of root dentin, decreasing the fracture load of the post may result in failure of the restoration. From a clinical perspective, the flexural strength of fiber posts should be balanced against the fracture load in order to select a fiber post suitable for each clinical situation (Zicari et al. 2013a).

When posts and dentin have a *similar elastic modulus* (*rigidity*), such as with fiber posts, posts with smaller diameter are associated with better stress distribution (Al-Omiri et al. 2011).

6.3.3 Post Shape

Posts are available in a variety of shapes (Fig. 6.5) – parallel with notched surface, parallel with smooth surface, parallel with threads, tapered with notched surface, tapered with smooth surface, and tapered with threads (Smith et al. 1998). Notched parallel posts are the most retentive of the passive prefabricated metal posts.

Changing a post-hole preparation from tapered to parallel-sided weakens the tooth (Lang et al. 2006). Although previous studies have implied that the retentive strength of posts increased with the use of parallel posts (Cohen et al. 1992; Morgano 1996; Teixeira et al. 2006), a cylindrical post without convergence weakens the apical area of the root that could lead to root fracture (Morgano 1996).

The use of *tapered fiber posts* over parallel posts is recommended.

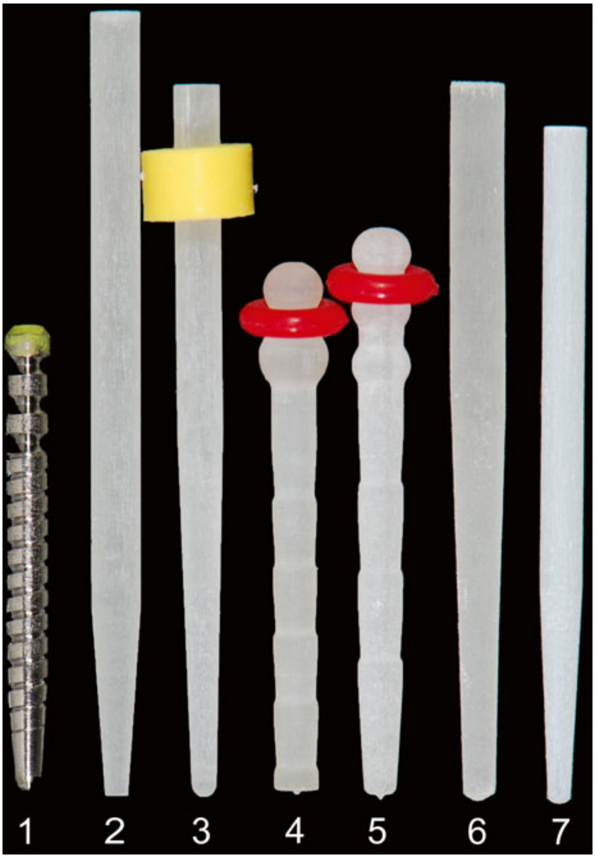

Fig. 6.5 Sample of prefabricated posts currently available *1*, Tenax (Coltene); *2*, GC Fiber Post (GC Co.); *3*, RelyX Fiber Post (3M ESPE); *4*, Parapost Fiber Lux (Coltene); *5*, Parapost Taper Lux (Coltene); *6*, White Post (FGM); *7*, Rebilda Post (VOCO GmbH)

6.4 Composition of Fiber Posts

The introduction of the first fiber posts in dentistry, carbon fiber-reinforced resin posts (or carbon fiber posts by Duret et al. 1990), was the milestone that changed some principles behind the restoration of endodontically treated teeth. Originally, carbon fiber posts were made of a matrix based on epoxy resin (64 % by weight) reinforced by unidirectional carbon/graphite fibers with a diameter of 8 μm (Torbjörner et al. 1996). However, carbon fiber posts are dark, therefore lacking cosmetic qualities. Carbon fiber posts were the first acceptable alternative to cast posts and to prefabricated metal or zirconia posts. Post-retained crowns using a carbon fiber post exhibited properties comparable with, and in some cases better than, those of other existing prefabricated posts at least in short-term studies (King and Setchell 1990).

One of the carbon fiber posts currently available in the US market is CF Carbon Fiber Post (J. Morita, USA) (Fig. 6.6a). The diameter of its fibers is 7.25 μm (Fig. 6.6b). White and translucent posts made of glass or silica fibers have been

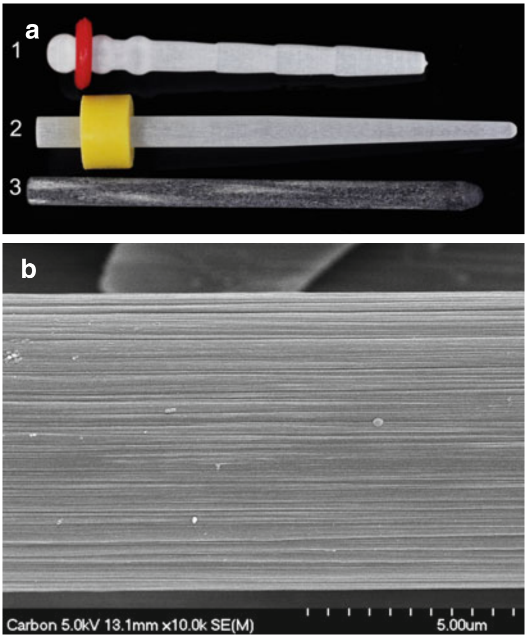

Fig. 6.6 (**a**) Different fiber posts. (*1*) Size 5 Parapost Taper Lux (Coltene), (*2*) Size 2 RelyX Fiber Post (3M ESPE), (*3*) Size L2, CF Carbon Fiber Post size L2 (J. Morita USA) (**b**) Scanning electron micrograph depicting an individual carbon fiber (CF Carbon Fiber Post, J. Morita USA). Original magnification = ×10,000

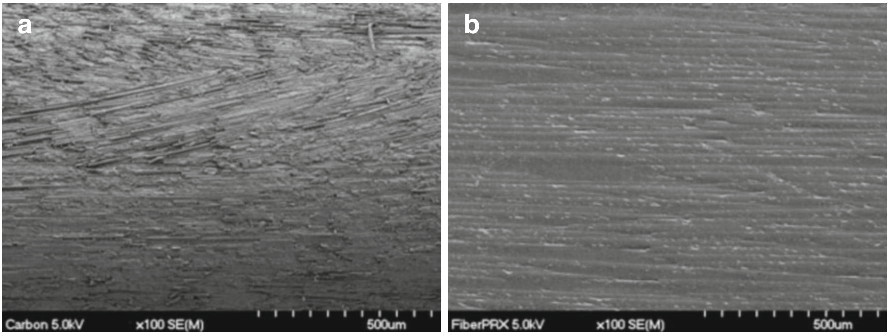

Fig. 6.7 (**a**) Scanning electron micrograph depicting the side view of a carbon fiber post (CF Carbon Fiber Post, J. Morita USA). Original magnification = ×100. (**b**) Scanning electron micrograph depicting the side view of a glass fiber post (RelyX Fiber Post, 3M ESPE). Original magnification = ×100

introduced to replace unaesthetic carbon fiber posts with materials with better esthetic qualities (Lassila et al. 2004). Glass fibers have a lower elastic modulus (lower rigidity) than that of carbon fibers (Lassila et al. 2004). Figure 6.7 shows the differences between the surface morphology of a carbon fiber post (Fig. 6.7a) and that of a current glass fiber post (Fig. 6.7b). Current glass fiber posts are translucent, made of a high volume percentage of continuous stretched unidirectional reinforcing glass fibers embedded in a polymer matrix, which keeps the fibers together (Fig. 6.8). The fiber–matrix ratio ranges from 40 to 65 % (Zicari et al. 2013a). The

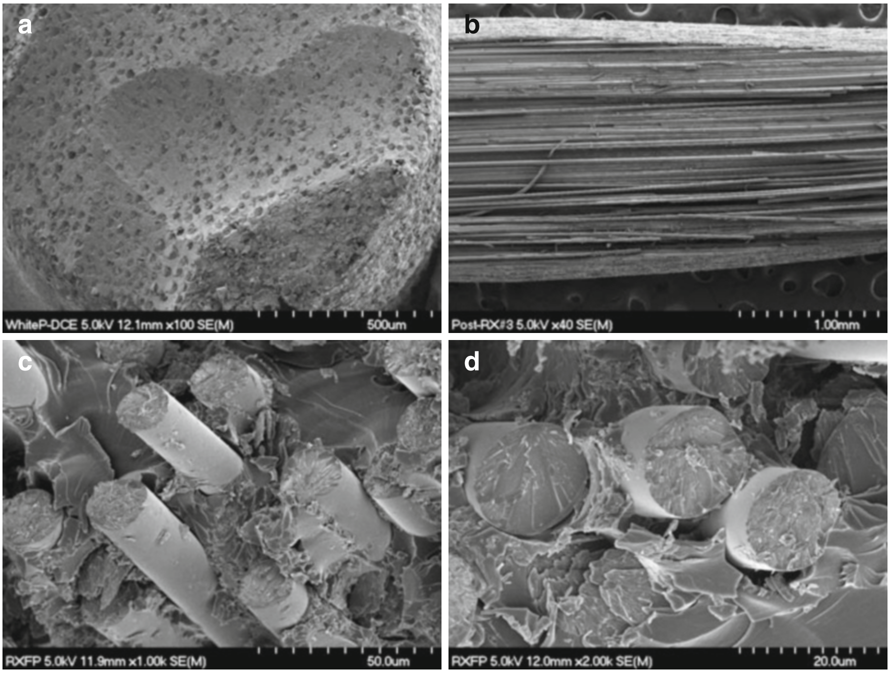

Fig. 6.8 (**a**) Scanning electron micrograph depicting a cross section of the coronal aspect of a glass fiber post (White Post DC-E, FGM). Original magnification = ×100. (**b**) Scanning electron micrograph depicting a longitudinal section of a glass fiber post (RelyX Fiber Post, 3M ESPE). Original magnification = ×40. (**c**) Scanning electron micrograph depicting a glass fiber post sectioned with a diamond bur (RelyX Fiber Post, 3M ESPE). Original magnification = ×1,000. (**d**) Scanning electron micrograph depicting a glass fiber post sectioned with a diamond bur (RelyX Fiber Post, 3M ESPE). Original magnification = ×2,000

resin matrix usually contains epoxy and/or methacrylate resin with high degree of conversion in a highly cross-linked structure, to which fillers and radiopaque agents may be added as well (Zicari et al. 2013a). Some post systems may also contain PMMA chains of high molecular weight. The matrix is responsible for the fiber composite high mechanical strength and distributes stresses between fibers (Lee and Peppas 1993). Fibers are responsible for resistance against flexure, while the resin matrix provides resistance against compression stress and may interact with functional monomers contained in the adhesive cements (Grandini et al. 2005). As described in Chap. 4, electrical glass (E-glass) is a commonly used glass type. Additionally, glass fiber posts can also be made of quartz fibers. Quartz is pure silica in crystallized form (Lassila et al. 2004).

Epoxy resins have long been known for their moisture absorbance (Antoon et al. 1981), which causes degradation (Lee and Peppas 1993). Grant and Bradley (1995) found a 17 % decrease in transverse tensile strength of carbon fiber-reinforced materials, also associated with degradation after moisture absorption. Storage in water significantly decreased both flexural modulus and strength for the carbon fiber posts. Fatigue test resulted in an additional significant reduction of flexural modulus and strength for both the dry and the water-saturated posts. Failures occur mainly in the fiber–matrix interface and as microcracks within the matrix. A reduced adhesion between fibers and matrix as well as matrix cracking was noticed both after water storage and thermocycling (Torbjörner et al. 1996).

For glass fiber posts, thermocycling decreases the flexural modulus by approximately 10 %. Strength and fracture load decreased approximately 18 % as a result of thermocycling (Lassila et al. 2004). A decrease in mechanical properties is taking place during 30 days of water storage and is caused by plasticization of the polymer matrix by water. Due to the different elastic modulus of fibers and resin matrix, stresses normally develop at the interface between fiber and matrix. Vallittu (2000) reported that the quality of the fiber–matrix interface affects the mechanical properties of fiber-reinforced composite (FRC) materials. *Without adequate adhesion between these two components*, *fibers act as voids in the resin matrix*, *thereby weakening the fiber resin composite*.

6.5 Why Fiber Posts?

Some previous studies have focused on the effect of the fiber–matrix ratio (surface occupied by fibers per square millimeter) on the flexural properties of fiber posts. Zicari et al. (2013a) studied the structural characteristics of different fiber posts, including density of fibers, diameter of fibers, fiber–matrix ratio, and distribution of fibers. They found no correlation between these parameters and flexural strength. Grandini et al. (2005) reported no correlation between the fatigue resistance exhibited by fiber posts and their structural characteristics, which included fiber diameter, fiber density, and the surface occupied by fibers per square millimeter of post surface. Seefeld et al. (2007) found a strong and significant linear correlation between the fiber–matrix ratio and the flexural strength of fiber posts. The results of these studies were somewhat contradictory.

When comparing flexural strength of posts with similar dimensions, specific posts perform significantly better than others. For some of them, this might be due to the strengthening effect of zirconia fillers (Zicari et al. 2013a) that are spread among fibers in some fiber posts currently available. When post-cement interfaces are observed under the backscattered field-emission scanning electron microscope (Perdigão, unpublished observations) (Fig. 6.9), filler particles are observed in the matrix of specific fiber posts (Fig. 6.9b) that correspond to those mentioned by Zicari et al. (2013a).

6.5.1 Fiber Posts Versus Metal Posts

Many in vitro studies have shown that fiber posts possess some advantages compared to metal posts due to the modulus of elasticity of the former being closer to that of dentin (Lassila et al. 2004; Zicari et al. 2013a, b). However, the modulus of a material is only one parameter influencing stress development.

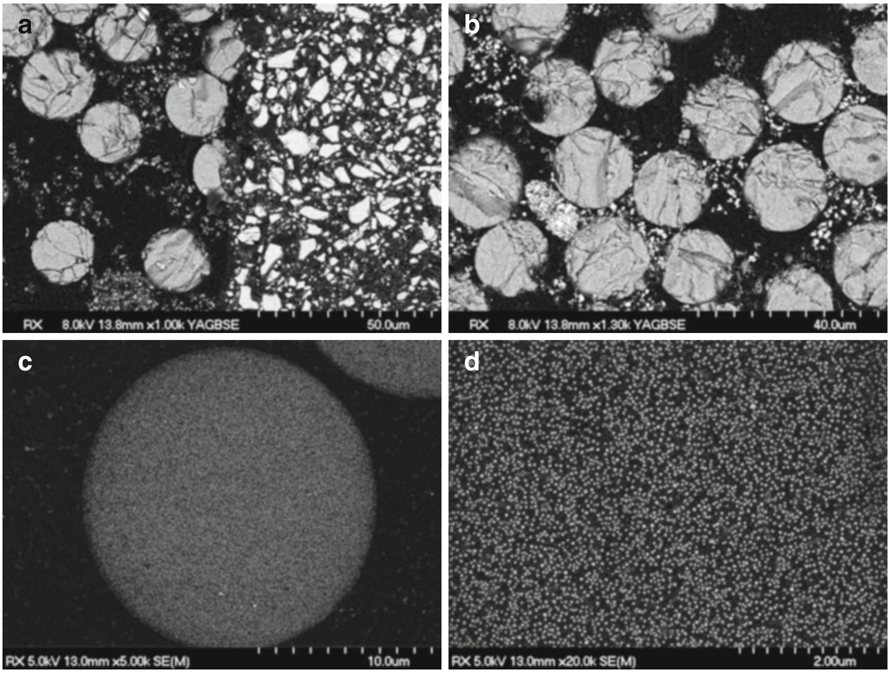

Fig. 6.9 (**a**) Scanning electron micrograph depicting an interface between a RelyX Fiber Post (3M ESPE) and a self-adhesive resin cement. Original magnification = ×1,000. (**b**) Scanning electron micrograph depicting a RelyX Fiber Post (3M ESPE). Original magnification = ×1,300. (**c**) Scanning electron micrograph depicting an individual glass fiber in a RelyX Fiber Post (3M ESPE). Original magnification = ×5,000. (**d**) Higher magnification of the individual fiber shown in C. Original magnification = ×20,000

Fiber posts *induce lower stresses than metal posts* (Pegoretti et al. 2002; Santos et al. 2010). Additionally, *fractures are less likely to occur in the root in endodontically treated teeth restored with fiber posts* (Santos et al. 2010). A literature review from 1984 to 2003 comparing modes of failure concluded that significantly more favorable failures occurred with prefabricated fiber post systems than with prefabricated and custom-cast metal post systems (Fokkinga et al. 2004).

The mechanical response of a glass fiber post to loads applied externally was calculated by finite element analysis (FEA) (Pegoretti et al. 2002). The resulting stress was compared with that obtained with a cast metal post and a carbon fiber post and with the response of a natural tooth. *The cast post and core produced the greatest stress concentration at the post-dentin interface*. On the other hand, the fiber posts presented high stresses in the cervical region due to their flexibility. The *glass fiber post resulted in the lowest peak stresses inside the root because its stiffness is similar to that of dentin*. Except for the force concentration at the cervical margin, the glass fiber post induced a stress field quite similar to that of the natural tooth (Pegoretti et al. 2002).

Cast metal posts have shown high survival rates after 10 years (Gómez-Polo et al. 2010). Compared to fiber posts, *cast metal dowels have the highest resistance to fracture*, but may result in non-repairable fractures when used to restore wide root canals. Fractures that occurred with fiber posts and relined posts provided adequate fracture resistance with increased incidence of repairable fractures (Aggarwal et al. 2012). A recent meta-analysis (Zhou and Wang 2013) also concluded that cast posts had higher fracture resistance than fiber posts. However, *teeth with* **cast metal posts** *had catastrophic failures*, *such as oblique or horizontal fractures in the middle third of the root or vertical fractures of the root. The failures that occurred with the* **fiber posts** *were repairable*, *such as fractures at the cervical third of roots or the cores* (Zhou and Wang 2013).

Cast metal posts and fiber posts can also be used for restoring weakened roots. Bonding cast posts to the tooth structure has a significant effect on compensating for the lack of a ferrule on endodontically treated teeth (Dorriz et al. 2009). When roots were weakened by excess widening of the root canal at the coronal third, fiber posts with a wider cervical emergence diameter were the best clinical solution compared to cast metal posts, even though the prognosis of the restored tooth is questionable. *Fractures that occurred with* **fiber posts** *were repairable* (Wandscher et al. 2014).

6.5.2 Fiber Posts Versus Zirconia Posts

Asmussen et al. (1999) compared some physical properties of carbon fiber posts with those of zirconia and titanium posts. *The stiffness of zirconia posts was five times greater than that of carbon fiber posts*. The authors described zirconia posts as being brittle without ductility. Carbon fiber posts were described as having elastic limits that were “lower than the strength value, indicating a certain amount of plastic behavior.”

Akkayan and Gülmez (2002) compared the effect of different prefabricated posts (titanium, quartz fiber, glass fiber, and zirconia posts) on the fracture resistance and fracture patterns of crowned endodontically treated teeth. Posts were luted with an etch-and-rinse adhesive and a dual-cure resin cement. All teeth were restored with composite cores; metal crowns were cemented with glass–ionomer cement. Teeth restored with quartz *fiber posts* resulted in significantly higher failure loads compared to teeth restored with the other three posts. *Repairable fractures* were observed in teeth restored with *fiber posts. Zirconia posts* induced more *catastrophic root fractures*, while teeth restored with *fiber posts were less prone to fracture* than teeth restored with titanium or zirconia posts (Akkayan and Gülmez 2002).

The survival rates and fracture strength of endodontically treated maxillary incisors with moderate coronal defects restored with different post-and-core systems and fatigued in the artificial mouth were significantly lower for zirconia posts with composite cores, which led the authors not to recommend zirconia posts for clinical use (Butz et al. 2001). The survival rate of zirconia posts was significantly lower than that of fiber posts (Mannocci et al. 1999). In this study, fiber posts reduced to a minimum the risk of root fractures of teeth restored with composite cores and ceramic crowns. While only one fracture occurred in each fiber post group, six failures were observed (one crown fracture and five root fractures + post fractures) in the zirconia post group after intermittent loading in a wet environment (Mannocci et al. 1999).

> Fiber posts reduce the risk of root fractures of endodontically treated restored teeth.

6.6 Surface Treatment of Fiber Posts

Several chemo-mechanical surface treatment methods have been used to increase the bonding properties of the surface of fiber posts – hydrofluoric acid, potassium permanganate, sodium ethoxide, sandblasting, and hydrogen peroxide. All these methods have resulted in an interpenetrating network between the treated surface of the fiber post and the composite resin used as luting agent (Monticelli et al. 2006). The penetration of the composite luting material into the spaces between fibers may be a result of increased surface roughness. In fact, it has been shown that hydrofluoric acid, potassium permanganate, sodium ethoxide, and sandblasting all increase post surface roughness (Mazzitelli et al. 2008).

Although results of different studies are contradictory in some cases, immersion in hydrogen peroxide is a promising method to enhance adhesion to fiber posts. Yenisey and Kulunk (2008) studied the effect of hydrogen peroxide and methylene chloride on the shear bond strengths of fiber posts to composite resin. The surface treatment of fiber posts with 10 % hydrogen peroxide for 20 min significantly enhanced the mean shear bond strengths due to the ability of hydrogen peroxide to dissolve the epoxy resin matrix used in each post. Application of methylene chloride to the fiber post surfaces for 5 s was not effective in increasing the shear bond strengths. Similar surface treatments were tested by Elsaka (2013). The application of 30 % hydrogen peroxide or methylene chloride for 5 or 10 min enhanced the adhesion between fiber posts and resin core materials. In another study both 24 and 50 % hydrogen peroxide increased the mean bond strengths of resin to fiber posts, irrespective of the application time (1 min, 5 min, or 10 min). Non-treated posts displayed a relatively smooth surface without fiber exposure. Application of hydrogen peroxide increased the surface roughness and exposed individual fibers (de Sousa Menezes et al. 2011).

Mazzitelli et al. (2012) used two self-adhesive resin cements and five post surface treatments, including silane, 10 % hydrogen peroxide, and sandblasting with silicatization. For one of the posts, the mean pushout bond strengths were similar for all surface treatments. For one of the self-adhesive cements, only silanization improved the pushout bond strengths. Zicari et al. (2012) reported a significantly

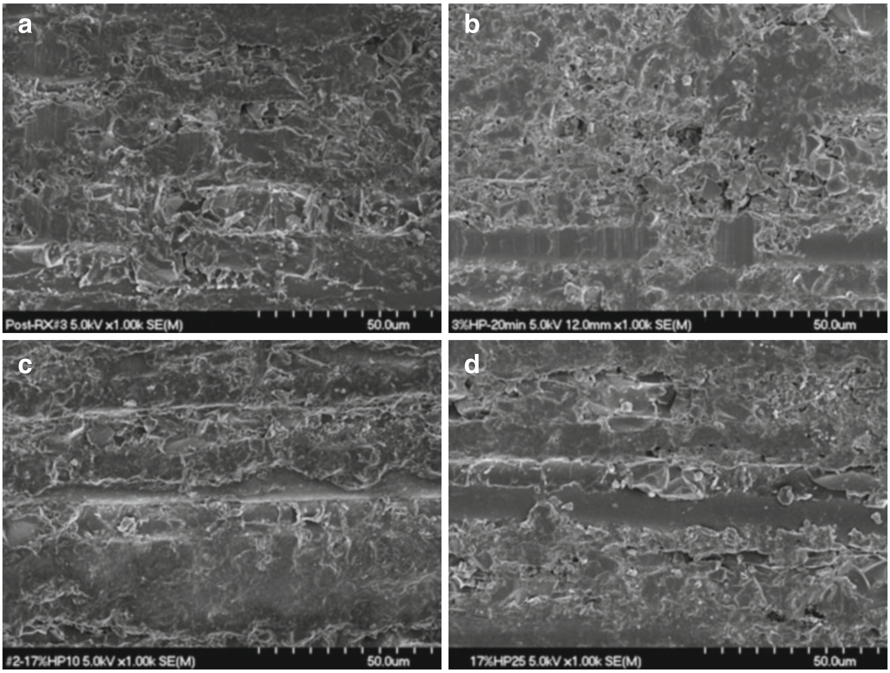

Fig. 6.10 Scanning electron micrographs of the surface of RelyX Fiber Post (3M ESPE). Original magnification = ×1,000. (**a**) No treatment, (**b**) treated with 3 % hydrogen peroxide for 20 min, (**c**) treated with 17 % hydrogen peroxide for 10 min, (**d**) treated with 17 % hydrogen peroxide for 25 min

higher mean pushout bond strength when the post surface was pretreated with sandblasting and silicatization compared to when the post surface was treated with silane or left untreated.

In our laboratory we have been unable to confirm the ability of hydrogen peroxide to transform the surface of fiber posts (Fig. 6.10). Chapters 5 and 9 discuss the post surface treatment in more detail.

6.7 Frequent Myths

6.7.1 Posts Reinforce the Residual Tooth Structure

The primary purpose of a post is to retain a core used to retain the definitive prosthesis. Several authors within the last 40 years have reported that metal dowels do not reinforce endodontically treated teeth when luted with traditional acid–base cements. However, when a prefabricated metal post is luted into the root canal with a resin-based luting cement, the resistance to fracture increased significantly compared to when zinc phosphate was used (Mendoza et al. 1997).

More recently, with the advent of fiber posts and simplified adhesive luting techniques, several authors have described a reinforcement effect from luting fiber posts into the root canal with adhesive materials (Carvalho et al. 2005; Goncalves et al. 2006; Hayashi et al. 2006; D'Arcangelo et al. 2010). Mangold and Kern (2011) evaluated the influence of fiber posts on the fracture resistance of endodontically treated mandibular premolars with varying degrees of substance loss. Post placement had a significant influence on the fracture resistance of endodontically treated premolars; however, the fracture resistance was dependent on the number of residual coronal dentin walls. Placement of a fiber post had a significant influence on the fracture resistance only when fewer than two cavity walls remained.

In summary, there is evidence that adhesively luted fiber posts reinforce the residual tooth structure.

6.7.2 Post Fit Influences Retention

Costa et al. (2012) measured fracture resistance of endodontically treated human premolars restored with bonded fiber posts and a composite buildup. The use of accessory thinner posts to fill in the space between the primary post and the root canal walls did not increase the fracture resistance of teeth. In another in vitro study, post fit did not have a significant influence on fracture resistance, irrespective of the post length, after thermomechanical loading (Büttel et al. 2009). Perdigão et al. (2007) used a small tapered fiber post size with a diameter of 1.50 mm at the coronal end and 0.90 mm at the apical end. The post spaces were prepared with drills of increasingly wider diameter. The diameter of the post space did not significantly affect the pushout bond strengths (Fig. 6.11). Ferrari et al. (2012) reported a lower 6-year failure risk in teeth restored with prefabricated posts than with customized posts.

The adaptation of the fiber post to the root canal walls does not seem to play a significant role in post retention.

6.7.3 The Coronal Restoration Has the Greatest Impact on the Clinical Success of the Endodontically Treated Tooth

As discussed in Chap. 1, Gillen et al. (2011) performed a systematic review on the impact of the quality of the coronal restoration versus the quality of the root canal filling on the success of the endodontic treatment. These authors found that either

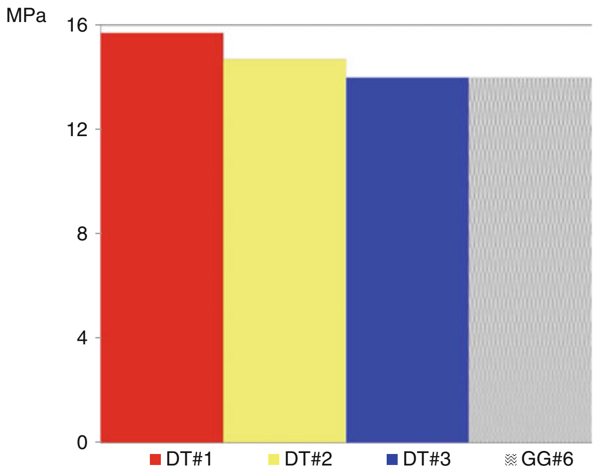

Fig. 6.11 Mean pushout bond strengths (MPa) (adapted from Perdigão et al. 2007) A D.T. Light Post size 1 (Bisco, Inc.) was used for all groups. This post has a diameter of 1.50 mm at the coronal end and 0.90 mm at the apical end. The luting system used was One-Step Adhesive (Bisco, Inc.) and Post Cement Hi-X Self-Cured Resin Cement (Bisco, Inc.). DT#1, #1 D.T. Drill (Bisco Inc.); DT#2, #2 D.T. Drill (Bisco Inc.); DT#3, #3 D.T. Drill (Bisco Inc.); GG#6, #6 Gates-Glidden

the quality of the coronal restoration or the quality of the root canal filling contributes equally to a successful outcome. The odds for healing of apical periodontitis increase with both adequate root canal treatment and adequate restorative treatment.

6.7.4 A Wider Post Space Provides Greater Post Retention Because a Thicker Post Can Be Used

Stress to the root walls generally increases as post diameter increases and as the vertical load increases (Mattison 1982). Over-instrumentation of access preparation and root canals may result in tooth fractures. When endodontically treated teeth were restored with small diameter stainless steel posts, resistance to fracture increased in comparison with the resistance to fracture obtained with larger post sizes (Trabert et al. 1978). Furthermore, varying the dowel diameter has no significant affect on the retentive abilities of metal dowels (Standlee et al. 1978). The use of smaller diameter posts reduces the stresses exerted upon root dentin walls and limits the amount of tooth material removed during preparation. Consequently, the restorative dentist will have more tooth structure to work on, which may aid the operative procedure by limiting the amount of tooth preparation (Mattison 1982). More recently it has been reported that fiber posts with the smallest diameter result in higher flexural strength (Zicari et al. 2013a).

Overpreparation of the post space and larger posts produce no greater reinforcement but actually decrease the resistance to fracture (Trabert et al. 1978; Mattison 1982). Postendodontic tooth fractures might occur because of the loss of tooth structure and stresses caused by restorative procedures such as access cavity preparation, instrumentation and irrigation and obturation of the root canal, post-space preparation, and coronal restoration, and from inappropriate selection of tooth abutments for prostheses (Tang et al. 2010). Potential tooth fractures might be reduced if practitioners are aware of controllable and noncontrollable risks during dental treatments.

In summary, it is not recommended to prepare wider post spaces with the sole goal of inserting a thicker fiber post, as removal of sound tooth structure may be detrimental for the longevity of the endodontically treated tooth.

6.7.5 Translucent Fiber Posts Transmit Light to Cure the Cement in the Root Canal

The available evidence shows otherwise, as translucent posts have limited light transmission (Teixeira et al. 2006; Faria e Silva et al. 2007). Two fiber posts, DT Light Post (Bisco Inc.) and FRC Postec Plus (Ivoclar Vivadent) revealed a light transmission of 10.2 % and 7.7 %, respectively (Kim et al. 2009). Another fiber post, SnowPost (Danville Materials), exhibited a significantly lower value of 0.5 %. The degree of conversion of the luting cement Variolink II (Ivoclar Vivadent) ranged from 32.78 to 69.73 % depending on the depth and type of post (Kim et al. 2009).

There is a significant reduction of the quantity of light transmitted through translucent fiber posts as the depth increases in the root canal. Even without the post, the intensity inside the canal decreases to levels that are insufficient for polymerization, especially in the apical third (dos Santos Alves Morgan et al. 2008).

Translucent posts do not transmit enough light to polymerize resin cements in the apical area of the post space.

6.7.6 Notched Fiber Posts Result in Better Retention than Smooth Fiber Posts

Retention notches (serrations) may decrease fatigue resistance (Grandini et al. 2005). The retention of glass fiber posts is unaffected by surface serrations but is influenced by the resin cement type (Soares et al. 2012). Serrations along the post length may act as points of stress concentration and weaken the post (Zicari et al. 2013a).

Notched fiber posts are not recommended because they are physically weaker than smooth-sided posts.

6.7.7 The Type of Root Canal Sealer Affects Bonding to Root Canal Dentin

When posts are cemented in teeth in which the canal is obturated before post-space preparation (sealer-contaminated dentin is removed by the post-space preparation procedure), the retention of posts is higher than when the canal is obturated after post-space preparation in which contaminated dentin might remain (Boone et al. 2001). The type of sealer, with or without eugenol, and time of cementation have no effect on post retention. Achieving a clean root dentin surface during mechanical post-space preparation is crucial for post retention when a resin-based cement is used (Boone et al. 2001). Kurtz et al. (2003) measured pushout bond strengths of posts cemented in the root canal that had been obturated with a eugenol-containing sealer or a eugenol-free sealer. There were no differences in bond strengths.

The composition of the root canal sealer used during the root canal obturation (with or without eugenol) may not affect the retention of fiber posts cemented with adhesive and resin cement.

6.7.8 A Silane Solution Must Be Applied Onto the Post Surface Prior to Luting

The use of a silane solution to enhance the bonding characteristics of fiber posts is controversial. While some authors have reported increased bond strengths (Goracci et al. 2005), most peer-reviewed research publications on the subject have reported that the use of a silane solution chairside does not improve the bonding ability of fiber posts to root canal dentin (Perdigão et al. 2006; Bitter et al. 2007; Wrbas et al. 2007a, b; Tian et al. 2012). As most posts are made of an epoxy resin, current silane solutions used in dentistry are compatible with methacrylate-based resins but not with epoxy resins. However, silane application may improve the adhesion of fiber posts luted with a self-adhesive resin cement (Leme et al. 2013). The mechanism is unclear, but it may have to do with an increase in wettability of the surface of the post.

6.7.9 Luting Fiber Posts in the Root Canal Does Not Provide an Adequate Sealing Because Fiber Posts May Flex Under Occlusal Load

Sealing the root canal against coronal bacterial leakage from the oral environment is important for clinical success of the restored endodontically treated tooth.

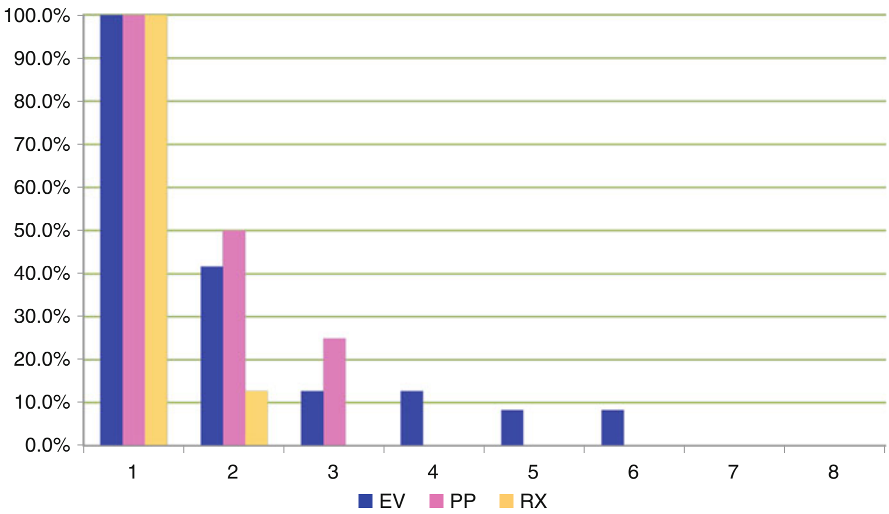

Fig. 6.12 Diagram adapted from Santos et al. (2009) depicting the percentage of dentin disks with silver penetration after sectioning the roots of endodontically treated premolars restored with adhesively luted fiber posts. Specimens were challenged with ammoniacal silver nitrate prior to sectioning. Disk #1 corresponds to the most occlusal disk, while disk #8 corresponds to the most apical disk. Note that all systems allowed infiltration of silver to 12/12 of the most occlusal root sections (disk #1). EV did not seal the root canals well as it resulted in penetration of silver ions down to disk #6. RX only allowed permeation of silver ions in 2 out of 12 disks. No other disk located apically to disk #2 was infiltrated with silver for the RX system. EV, everStick POST (StickTech Ltd) + ParaCem Universal DC (Coltene); PP, ParaPost Fiber Lux (Coltene) + ParaCem Universal DC (Coltene); RX, RelyX Fiber Post (3M ESPE) + RelyX Unicem (3M ESPE)

Recently, the advent of self-adhesive resin cements has made it possible to lute fiber posts in the root canal without the need to acid etch or apply a separate adhesive system. RelyX Unicem (3M ESPE) used with fiber posts in vitro sealed the coronal part of the root canal better than conventional resin cements (Santos et al. 2009) (Figs. 6.12 and 6.13). Additionally, RelyX Unicem (3M ESPE) results in higher pushout bond strengths between post and root canal dentin than other cements (Bitter et al. 2012; Zicari et al. 2012). The same luting material has resulted in excellent in vitro sealing on the coronal aspect of the root canal after simulated clinical use (thermal and mechanical fatigue) (Bitter et al. 2011; Bitter et al. 2012). This topic will be explored in more detail in other chapters.

6.8 Advantages and Disadvantages of Fiber Posts

In the last few decades, fiber-reinforced posts have been increasingly used to restore endodontically treated teeth. Dentists have quickly accepted fiber posts as a viable direct restorative procedure to retain the core buildup material. The advantages and disadvantages of fiber posts are listed in Tables 6.2 and 6.3.

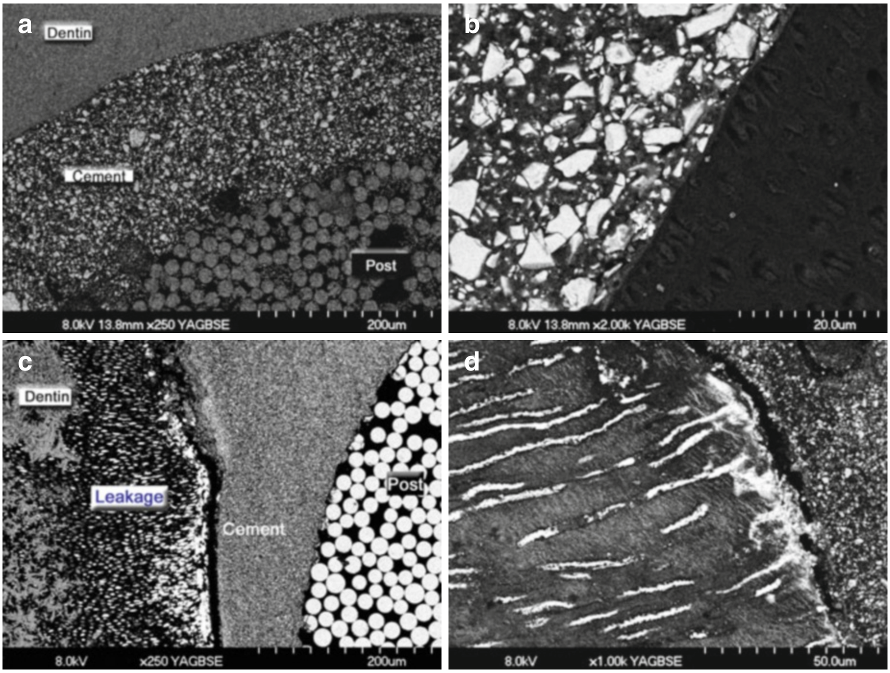

Fig. 6.13 Scanning electron micrographs (backscattered mode) showing root sections with fiber posts cemented into the root canal. After luting the post, roots were challenged with ammoniacal silver nitrate following the protocol of Santos et al. (2009). (**a**) Interfaces formed with RelyX Fiber Post (3M ESPE) luted with a self-adhesive resin cement and root dentin. Nanoleakage of silver ions was not detected in this specimen. Original magnification = ×250. (**b**) Interface formed with a self-adhesive resin cement and root dentin. No nanoleakage was observed in this interface. Original magnification = ×2,000. (**c**) Interfaces formed with RelyX Fiber Post (3M ESPE), luted with a conventional resin cement applied with a self-etch adhesive, and root dentin. Silver ions infiltrated the entire interface (nanoleakage). Original magnification = ×250. (**d**) Interface formed with a conventional resin cement applied with a self-etch adhesive and root dentin. Silver ions infiltrated the interface and the dentinal tubules. Original magnification = ×1,000

6.9 Restorability

The restorability of a tooth that is compromised by a caries lesion and/or extensive restoration must be decided prior to referring the patient to an endodontics specialist. Often teeth are deemed unrestorable after the root canal treatment has been complete (Figs. 6.14 and 6.15). The preservation of coronal walls is one of the most critical factors for the success of restored endodontically treated teeth. The absence of all coronal walls results in the worst possible circumstances for the survival of the restored tooth (Cagidiaco et al. 2008; Ferrari et al. 2012). In Baraban (1967) wrote “the basic objective is to restore the tooth to fulfill the functional and esthetic demands to which it will be subjected.” The first questions when doing a treatment plan is whether there is enough remaining sound tooth structure to support the core

Table 6.2 Advantages of fiber posts

Fiber posts have a modulus of elasticity similar to that of dentin (Zicari et al. 2013a)
Fiber posts result in greater bond strength to root dentin than zirconia posts (Kurtz et al. 2003). The adaptation provided by zirconia posts is deficient (Dietschi et al. 1997)
Fiber posts are less likely to cause root fractures compared with metal or zirconia posts (Isidor et al. 1996; Akkayan and Gülmez 2002)
Forces absorbed by the core and fiber post are not transferred to the vulnerable root structure (Isidor et al. 1996; Pegoretti et al. 2002)
Posts that have a similar modulus of elasticity to dentin and smaller diameters are associated with better stress distribution (Al-Omiri et al. 2011)
Fiber posts are esthetic and biocompatible and can be easily trimmed
Bonded fiber posts may reinforce the root (Goncalves et al. 2006; Naumann et al. 2007), especially is the post surface is treated with sandblasting (Schmitter et al. 2006)
The increase in wall thickness of weakened roots using composite resins increases the root resistance to fracture (Goncalves et al. 2006)
Only one session to complete the buildup

Table 6.3 Disadvantages of fiber posts

Some fiber posts may flex under occlusal load leading to stresses and interfacial gaps
Prefabricated posts are cylindrical or tapered; they do not adapt well to the anatomy of root canals
Radiopacity is not ideal; variable radiopacity among different brands (Figs. 6.5 and 6.16)
Earlier generations of fiber posts were difficult to mask under all ceramic or composite restorations (Vichi et al. 2000)
Bonding between post and current resin-based luting materials is not ideal

and respective restoration. In case the tooth is not salvageable, and extraction followed by implant, fixed partial prosthesis or removal partial prosthesis is indicated.

As metal posts have high elastic modulus in comparison with that of dentin (Hicks 2008), the risks of root fracture and catastrophic failures with metal posts are increased (Zarone et al. 2006). The risk of catastrophic failure with fiber posts is reduced (Fernandes et al. 2003), and most failures associated with fiber posts are a result of post debonding and failure of the endodontic therapy (Ferrari et al. 2007; Rasimick et al. 2010).

However, few studies have compared fiber posts and cast metal posts to restore endodontically treated teeth with no remaining coronal wall. *The evaluation of the restorability* of a root canal treated tooth must encompass four crucial questions:

6.9.1 Have All Carious Tissues Been Removed?

The restorability must be evaluated only after removing existing restorations and carious enamel/dentin tissues (Fig. 6.14).

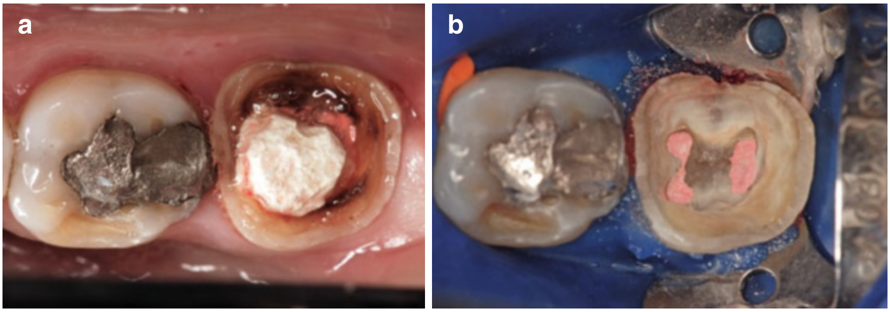

Fig. 6.14 (**a**) Endodontically treated mandibular second molar with carious tissues and a temporary restoration. All carious dentin and residual coronal restorative materials must be removed prior to deciding if the tooth is restorable. (**b**) The tooth was considered unrestorable using a fiber post and direct composite resin buildup, as no sound residual walls remained

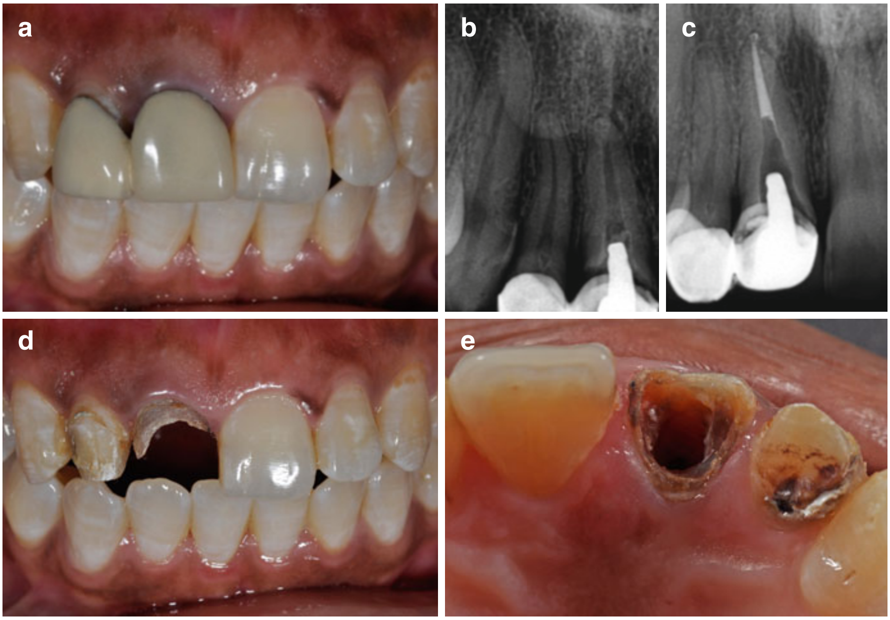

Fig. 6.15 (**a**) Frontal view of a clinical case of a patient referred for treatment to replace a porcelain-fused-to-metal FPD on the right maxillary central incisor and the right maxillary lateral incisor. This patient had just recently completed a root canal treatment on the right maxillary central incisor with the objective of replacing the two-element FPD. (**b**) Periapical radiograph before a root canal treatment was performed on the right maxillary central incisor. (**c**) Periapical radiograph after the completion of root canal treatment on the right maxillary central incisor. The preexisting FPD was cemented as a provisional restoration. (**d**) Frontal view after removing the provisional restorations. (**e**) Incisal view of right maxillary central incisor. At this point the tooth was deemed unrestorable under the circumstances of this clinical case

Fig. 6.16 Radiograph of the same posts shown in Fig. 6.5. *1*, Tenax (Coltene); *2*, GC Fiber Post (GC Co.); *3*, RelyX Fiber Post (3M ESPE); *4*, Parapost Fiber Lux (Coltene); *5*, Parapost Taper Lux (Coltene); *6*, White Post (FGM); *7*, Rebilda Post (VOCO GmbH)

6.9.2 Is There an Adequate Ferrule to Support the Foundation?

Rosen (1961) elegantly described a "extracoronal brace" as "a subgingival collar or apron of gold which extends as far as possible beyond the gingival seat of the core and completely surrounds the perimeter of the cervical part of the tooth. It is an extension of the restored crown which, by its hugging action, prevents vertical shattering of the root." This concept is now known as the *ferrule effect*.

An incomplete crown ferrule in maxillary incisors is associated with greater variation in load capacity and fracture pattern (Naumann et al. 2006). Increasing the ferrule height from 1 to 1.5 mm did not result in significant increase in the failure loads of teeth restored with fiber posts (Akkayan 2004). However, fracture thresholds were higher for all post systems when specimens were prepared with a 2.0-mm ferrule height (Akkayan 2004). Another study (Tan et al. 2005) demonstrated that central incisors restored with cast dowel/core and crowns with a 2-mm uniform ferrule were more fracture resistant compared to central incisors with nonuniform (0.5–2 mm) ferrule heights. Both the 2-mm ferrule and nonuniform ferrule groups were more fracture resistant than the group that lacked a ferrule. When the effects

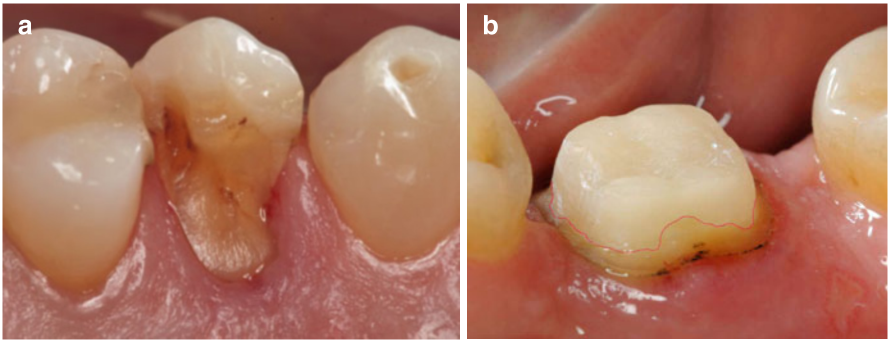

Fig. 6.17 (**a**) Maxillary first premolar fractured at the subgingival level. The ferrule effect (Rosen 1961) was not feasible in this case without orthodontic extrusion or periodontal crown lengthening surgery. (**b**) A 2-mm-high and 1-mm-thick collar of tooth structure was present in 90 % of the preparation perimeter. In spite of being considered an incomplete ferrule, we decided to proceed without the restorative treatment plan without tooth extrusion or crown lengthening, as no area of the crown margin would be located subgingivally

of post-core design and ferrule on the fracture resistance of root canal treated maxillary central incisors restored with metal ceramic crowns were tested, the group in which teeth had a 2-mm ferrule and were restored with a cast post-core and a porcelain-fused-to-metal crown resulted in the greatest fracture strength (Zhi-Yue and Yu-Xing 2003). It should be noted that resting coronal restorations on sound dental tissues affects stress distribution more than the type of core material or the length of the coronal post extension (Al-Omiri et al. 2011).

The clinical success improves considerably when a ferrule of at least 2.0 mm is present (Cagidiaco et al. 2008). A 3-year clinical study (Mancebo et al. 2010) included 45 teeth with ferrule (>2 mm height) and 42 teeth without ferrule (<2 mm height). The failure rate observed for teeth with ferrule was 6.7 %, while the failure rate in teeth without ferrule was 26.2 %. If the clinical situation does not permit a circumferential ferrule, an incomplete ferrule (Fig. 6.17) is considered a better option than a complete lack of ferrule (Juloski et al. 2012).

The 3-year survival rate of teeth restored with cast posts versus fiber posts was statistically similar in the absence of the ferrule effect (Sarkis-Onofre et al. 2014). Zicari et al. (2013b) evaluated the in vitro influence of a ferrule and the insertion of a fiber post on the fracture resistance of endodontically treated teeth restored with composite cores and lithium disilicate crowns, then subjected to cyclic fatigue loading. *The ferrule effect significantly increased the fracture resistance of the restored teeth*, *regardless the use of a post*. Teeth without ferrule effect restored without a fiber post had the lowest fracture resistance.

6.9.3 Has the Periodontal Status Been Evaluated?

Setzer et al. (2011) tested the hypotheses that preoperative factors can predict the long-term prognosis of molars requiring endodontic and restorative treatment for future prognostic investigations. Charts of 42 patients (age ranged from 19 to

87 years) with 50 individual endodontic treatments were randomly selected from a clinical database containing molar endodontic treatments with crown placement and a minimum of 4-year up to 6-year follow-up. Radiographs from baseline and follow-up were obtained, and available ferrule was calculated from bitewing radiographs. Other clinical parameters were recorded, including attachment loss, crown lengthening, furcation involvement, and mobility, among others. The presence of apical periodontitis was also evaluated. The only preoperative factors significant for the prognosis of the restored endodontically treated molars in these patients were related to preoperative periodontal conditions (Setzer et al. 2011). *The conclusions of this study are clinically relevant – a consultation with a periodontology specialist is recommended in case the periodontal condition is not deemed to be ideal*.

One of the most common clinical procedures performed to regain cervical ferrule and prevent the violation of the biological width is surgical crown lengthening. However, orthodontic extrusion should be considered rather than surgical crown lengthening in teeth with no coronal structure. If neither of the alternative methods can be performed, evidence suggests that a poor clinical outcome is very likely (Juloski et al. 2012).

6.9.4 What Is the Minimum Number of Residual Coronal Walls?

> In clinical studies up to 6 years, preservation of coronal walls reduced failure risk in endodontically treated premolars (Cagidiaco et al. 2008; Ferrari et al. 2012).

6.9.4.1 Anterior Teeth

In addition to post failure per se, the failure of teeth restored with intra-radicular posts can be related to tooth position; failures in post-retained crowns generally occur in the maxillary anterior region, where horizontal forces are greater than in other areas (Torbjörner and Fransson 2004). Colman (1979) advocated the need to place a dowel in endodontically treated anterior teeth regardless of the amount of residual tooth structure. The rationale for placing a dowel was to prevent cervical fracture in endodontically treated teeth, unless the tooth was out of the range of a functional occlusal relationship (Colman (1979). In fact, the cervical region of the restored endodontically treated tooth is subjected to the highest strain and stress concentrations (Sorrentino et al. 2007).

The placement of posts in endodontically treated incisors (Fig. 6.18) increases their resistance to fracture and improves the prognosis in case of fracture (Colman 1979; Smith and Schuman 1997). Salameh et al. (2008) assessed the fracture resistance and failure pattern of maxillary incisors restored using a microhybrid composite with or without placement of fiber posts, with different types of full crown coverage. The results of this study indicate *that the use of fiber posts in endodontically treated anterior teeth increases their resistance to fracture and improves the prognosis in case of fracture*. The presence/absence of the post had a significant influence on the proportion of restorable versus unrestorable fractures.

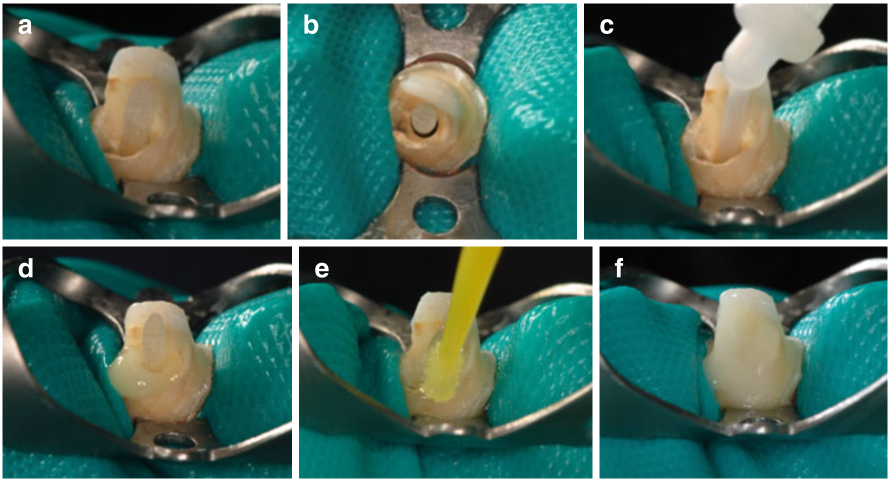

Fig. 6.18 Endodontically treated maxillary lateral incisor treatment planned for a full-coverage restoration. (**a**) Post was tried in after it was adapted and trimmed. (**b**) Incisal view showing the fit of the fiber post in the root canal. (**c**) In this particular clinical case, root and coronal dentin was etched with 35 % phosphoric acid for 15 s, rinse off with water, and dried with paper points, followed by a dual-cured dentin adhesive applied with a small brush applicator. This image shows the injection of a conventional dual-cure resin cement into the root canal. (**d**) The fiber post was then inserted through the dual-cure resin cement, and the excess of cement was removed with a brush. The external part of the cement was light cured for 40 s. (**e**) A new coat of dentin adhesive was applied and cured. (**f**) A dual-cure composite resin core buildup material was inserted and light cured

> Evidence suggests that *fiber posts* increase the fracture resistance of restored endodontically treated anterior teeth, even when teeth are restored with a full-coverage restoration.

6.9.4.2 Posterior Teeth

Vertical fracture of posterior teeth is a common postendodontic occurrence. Restored endodontically treated tooth must be able to withstand long-term masticatory forces, especially in the posterior region. Mangold and Kern (2011) evaluated the influence of a fiber post on the fracture resistance of endodontically treated premolars with varying degrees of substance loss. Placement of a fiber post has a significant influence on the fracture resistance when fewer than two cavity walls remain, but no significant influence when two or three walls are present (Mangold and Kern 2011). Mesio-occluso-distal (MOD) preparations represent the worst case in terms of fracture risk when restorations are inserted (Morin et al. 1984). Cusp deflection increases significantly in a premolar MOD preparation with an endodontic access compared to an MOD preparation without endodontic access (Panitvisai and Messer 1995). Composite restorations with fiber posts are more effective than composite alone in reducing the cuspal deflection in endodontically treated premolars in which the marginal ridges have been lost (Acquaviva et al. 2011).

For endodontically treated posterior teeth, the placement of fiber posts is necessary to improve fracture resistance even under full-coverage crowns (Salameh et al. 2007; Mangold and Kern 2011; Acquaviva et al. 2011) when fewer than two walls remain or when marginal ridges are missing.

6.10 Clinical Studies

Bonding to root dentin still represents a greater challenge than bonding to coronal dentin (Table 6.4). Carbon fiber posts were used by seven private practitioners to restore 236 teeth, 130 maxillary and 106 mandibular teeth, with a mean restoration time of 32 months (range 27–41). Five teeth (2 %) were extracted for reasons unrelated to the carbon post system. Periodontal conditions such as plaque accumulation, gingival health, bleeding on probing, and pocket depth around the teeth with carbon posts were similar to the control teeth. No dislodgment or root or post fractures were observed clinically or on radiographs. This study found promising results after 2–3 years of clinical (Fredriksson et al. 1998). A subsequent retrospective study evaluated the treatment outcome up to 7 years using the same group of patients. Five of the former seven private practitioners participated in the follow-up study, the number of subjects being reduced to 138. Thirty-nine of these were excluded due to insufficient data. For the remaining 99 subjects, data were collected from dental records. The mean follow-up time was 6.7 (five teeth were extracted during the previous study). The outcome was considered successful if the post and core showed no clinical or radiographic signs of technical failures. Sixty-four teeth (65 %) restored with the carbon fiber post system were successful after a mean time of 6.7 years. Thirty-two teeth were extracted due to fractures, periapical lesions, and periodontitis. Dislodgment of post was observed in three cases. After a mean time of 6.7 years,

Table 6.4 Bonding to root dentin – the challenges

Limited vision and access
Residual gutta-percha and endodontic sealer debris
Difficult to apply and cure adhesives in the root canal
Difficult to rinse etchants and dry excess water
Solvent in adhesive may not be completely evaporated
Potential oxidizing effect of NaOCl
Increased volume of luting cement to fill in space between post and root dentin wall
High C-factor (ratio of bonded to unbonded surfaces) may result in greater polymerization stress
Variations in tubule density
Deposition of transparent dentin

Carvalho et al. (2009), Ree and Schwartz (2010) the teeth restored with carbon posts had shorter survival times than those of previously documented cast posts (Segerström et al. 2006).

> Carbon fiber posts are not currently recommended for the restoration of endodontically treated teeth.

Ferrari et al. (2000) evaluated over 1,200 endodontically treated teeth restored with carbon posts and glass fiber posts during 1–6 years of service. They measured a 3.2 % failure rate not related with the posts – 25 posts debonded during removal of temporary restorations, and 16 teeth showed periapical lesions. Ferrari et al. (2007) evaluated 985 endodontically treated teeth restored with fiber posts that had been in service from 7 to 11 years. They found 79 failures, of which 39 were a result of endodontic failure, one caused by root fracture, one caused by fiber post fracture, 17 by crown dislodgments, and 21 due to post debonding. *The mechanical failures were related to the lack of coronal tooth structure*. The failures in these two studies highlight the importance of the clinical technique during the adhesion procedure, as well as the quality of the root canal sealing, as most failures were caused by endodontic failure, debonding of the post, and lost of the coronal restoration.

Another clinical study (Ferrari et al. 2012) examined the contribution of remaining coronal dentin and placement of a prefabricated versus a customized fiber post to the 6-year survival of endodontically treated premolars restored with a full-coverage restoration. A sample of 345 patients provided 60 premolars in need of endodontic treatment. The placement of a prefabricated or a customized post was shown to contribute significantly to the survival of endodontically treated restored premolars over a 6-year observation period. This contribution was more effective for the prefabricated fiber post than for the customized "anatomical" fiber post. *Regardless of the restorative procedure*, *preservation of at least one coronal wall significantly reduced the failure risk*.

Creugers et al. (2005) conducted a 5-year clinical study to test whether (1) the survival rate of cast post-and-core restorations is better than the survival of direct post-and-core restorations and post-free all-composite cores and (2) the survival of these buildup restorations is influenced by the remaining dentin height after preparation. Eighteen operators made 319 core restorations in 249 patients. The restorations involved were (1) cast post-and-core restorations, (2) direct post and composite core restorations, and (3) post-free all-composite cores. All restorations were made under single porcelain-fused-to-metal crowns. The type of post and core was not relevant with respect to survival. *The factor "remaining dentin height" had a significant effect on the survival of post-and-core restorations. As mentioned previously*, *the clinical success improves considerably when a ferrule of at least 2.0 mm is present* (Cagidiaco et al. 2008; Mancebo et al. 2010).

> Two common findings in most clinical studies are that the amount of *residual tooth structure* and the *ferrule* effect play a crucial role in the longevity of restored endodontically treated teeth.

6.11 Summary

The *clinical success* of a restored endodontically treated tooth depends on several factors:

1. Removal of all carious tissues
2. Quality of both the endodontic and the restorative treatments
3. Favorable periodontal and occlusion conditions
4. Preservation of radicular and coronal tooth structure
5. The presence of a ferrule that provides resistance form
6. Use of posts that do not transfer stresses to the residual tooth structure
7. Use of adhesive materials that attach the post to root canal dentin and seal the root canal
8. Meticulous use of materials and techniques backed by scientific evidence

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7 Adhesion to Root Dentin: A Challenging Task

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Abstract

The treatment of severely destroyed teeth involves quite often the placement of a fiberglass post into the root canal space as a means of retention for the final restorative procedure. The bonding of fiberglass posts into the root canal is a very challenging task in which several factors may influence the final outcome. This chapter summarizes (1) the several limiting factors that require the clinician's expertise to minimize bonding failures and (2) suggestions to overcome these limitations in a clinical setting.

The primary goal of applying adhesive materials in the root canal or pulp chamber space is to increase the retention of direct composite restorations or to retain a post and core in a tooth that has been weakened by loss of coronal tooth structure.

Luting fiber posts with adhesive techniques involves the use of a dentin adhesive system for hybridization of the dentin substrate and a resin cement to fill in the space between the root canal walls and the fiber post. There are two adhesive

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strategies that can be used – etch-and-rinse (ER) adhesives, which require previous phosphoric acid etching and rinsing, and self-etch (SE) adhesives. Typically, dual-cure resin cements are the material of choice due to limited access of light to the middle and apical root thirds. In alternative to the ER and SE strategies, the luting protocol may be carried out without a separate adhesive system. In this case, self-adhesive resin cements may be used.

Regardless of the type of material and/or technique, the bonding protocol to root dentin usually involves the same steps as used to bond to coronal dentin. However, an in vitro study with posts by Bouillaguet et al. (Bouillaguet et al. 2003) reported that lower bond strengths were achieved when posts were bonded in the root canal system compared to when posts were bonded to flat ground radicular dentin.

This difference is an example of several limiting factors that may require increased clinical awareness to minimize bonding failures. This chapter will discuss why bonding to the root canal is a challenging task prone to failures and how the bonding protocol can be adequately managed by the clinician.

7.1 Intraradicular Anatomy

Knowledge of root canal anatomy of the different teeth is essential in order to minimize the risk of complications such as loss of axial alignment or perforations when preparing the post space.

7.1.1 Root Anatomy

The shape of the canal of anterior maxillary teeth is usually oval at the cervical third and tends to become circular at the apical third. When it comes to anterior mandibular teeth, 40 % of them have two canals, which are usually circular in cross section. If only one canal is present, it is round in shape, broad buccolingually, and narrow mesiodistally. There may be a greater risk of perforation with this anatomical design. Therefore, preparation of a post space should only be done in cases with extensive crown loss.

Canines are single rooted, in most cases with a single straight canal. The risk of perforations is high during endodontic treatment near the thin apical third, but as the post space preparation does not reach such area, this feature does not seem to pose a problem for post placement.

The first maxillary premolar has two roots in 62 % of the cases, and the majority has two canals, which is different from the second upper premolar which is single-rooted tooth with only one broad canal buccopalatally. The lower premolars are usually single rooted and the canal is wide buccolingually.

In molars that do require a post, the post space should be prepared in the widest, straightest canal, which is the palatal canal in maxillary molars and distal canal in mandibular molars.

7.1.2 The Dentin Substrate

A very common doubt among clinicians is whether or not the composition of intraradicular dentin is similar to that of coronal dentin. As reported in a review of the literature (Schwartz 2006), few studies have investigated the composition and structure of intraradicular dentin, but they all agree that there are minor differences from coronal dentin.

As coronal dentin, intraradicular dentin is characterized by the presence of tubules that travel from the pulp to the cementum, with peritubular and intertubular dentin. The number of tubules greatly decreases towards the apical region of the intraradicular dentin; therefore, the ratio between peritubular and intertubular dentin varies significantly from the apical to the coronal third (Ferrari et al. 2000; Mjor et al. 2001).

In the apical third of the root there are fewer dentinal tubules (Ferrari et al. 2000; Mjor et al. 2001; Mannocci et al. 2004), and the dentin is irregular and may be devoided of dentin tubules (Mjor et al. 2001). When present, these tubules are often sclerotic and filled with minerals that resemble those from peritubular dentin (Paque et al. 2006), such as in transparent dentin.

The slightly differences between coronal and intraradicular dentins do not seem to be a barrier for bonding to radicular dentin, and, therefore, the likely differences in bonding to this substrate compared to coronal dentin might be caused by other factors that will be discussed in sequence.

7.2 Smear Layer

7.2.1 Endodontic Smear Layer

Whenever dentin is cut using hand or rotary instruments, the mineralized tissues are not shredded or cleaved but shattered to produce considerable quantities of debris. It is not different during instrumentation of the canal walls with endodontic files. A smear layer, which becomes tightly attached to the instrumented surface, is produced in a manner that prevents it from being rinsed off or scrubbed away easily (Pashley et al. 1988; Breschi et al. 2009).

This endodontic smear layer can form two zones: the first zone is 1–2 μm thick and consists of organic matter and dentin particles; the second zone extends into dentinal tubules to a depth that exceeds 10 μm (smear plugs) and is formed largely of dentin chips (Mader et al. 1984). The composition of this layer may vary significantly depending on the tooth substrate from which it is formed, the type of endodontic instrument used, and the method of irrigation. For instance, in the early stages of endodontic instrumentation, the smear layer contains a relatively high organic content because of the presence of necrotic and/or viable pulp tissue in the root canal (Violich and Chandler 2010).

The removal of the smear layer in endodontics is considered to be advantageous and highly desirable (Goracci et al. 2005; Breschi et al. 2009). This is due to the fact that the smear layer acts as a physical barrier interfering with adhesion and penetration of sealers into dentinal tubules. Therefore, irrigation solutions, capable of acting on the organic and inorganic elements of the smear layer, must be used during and after endodontic instrumentation.

Sodium hypochlorite (NaOCl) and ethylenediaminetetraacetic acid (EDTA) offer bactericidal, solvent, and chelating actions and are widely used for smear layer removal. Chlorhexidine is also a popular irrigant due to its long-lasting antibacterial effect through adherence to dentin; however, it does not dissolve organic material or remove the smear layer as do NaOCl and EDTA (Violich and Chandler 2010). The role of endodontic irrigants on the final bonding of fiber posts inside the root canals will be discussed later in this chapter.

7.2.2 Secondary Smear Layer

As reported in a review of the literature (Breschi et al. 2009), besides the smear layer formed by manual or rotary instrumentation of the root canal walls, the subsequent preparation of the post space using post drills results in an additional and even thicker smear layer. This layer is composed of debris and remnants of plasticized gutta-percha and sealer (Breschi et al. 2009) that significantly influenced the adhesion of fiber posts (Goracci et al. 2005). Such contaminants hinder chemical interaction and penetration of the luting agent to root dentin. In order to enhance post retention, a careful debridement of the post space walls should be performed prior to cementation (Goracci and Ferrari 2011), which is a critical and difficult step during post bonding.

The preparation of the root canals is usually performed with carbide drills, which are provided by the manufacturers of each fiber post system. It is likely that the rationale behind this choice is based on the fact that studies on coronal dentin have reported that higher bond strengths are achieved by using carbide burs rather than diamond cutting instruments (Sekimoto et al. 1999; Dias et al. 2004; Yiu et al. 2008). However, we may not expect the same outcome in the endodontically treated root walls. The smear layer produced by carbide burs inside the root canal is much more resistant to dissolution with phosphoric acid than that produced by a diamond bur of similar shape and size (Gomes et al. 2012).

This difference between coronal and intraradicular dentin may rely on the different compositions of the smear layers. In fact, the action of the drills used to remove the root-filling material to create post space produces a new smear layer rich in sealer and gutta-percha remnants that are plasticized by the frictional heat of the carbide drill that acts under inefficient water rinsing. This may impair the penetration and chemical action of the agents used to bond fiber posts (Fig. 7.1). Therefore, clinicians should be aware of it; further details in how to manage this will be discussed in the next chapter.

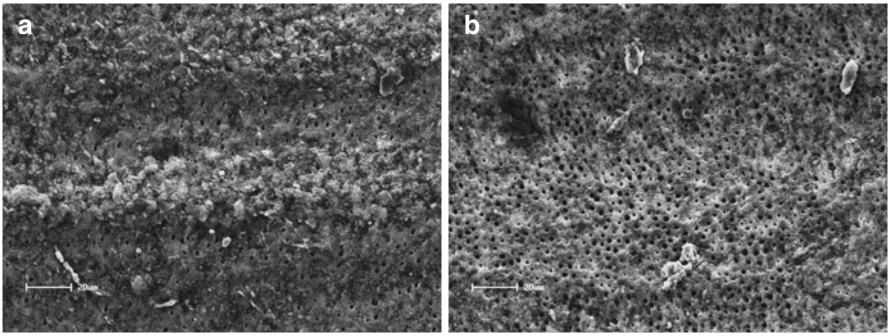

Fig. 7.1 Scanning electron micrographs of apical root dentin. In (**a**) the endodontic-treated root dentin was prepared with a carbide bur and conditioned with 37 % phosphoric acid. There are approximately 50 % of the dentinal tubules still obliterated with smear layer debris preventing effective bonding. In (**b**) the endodontic-treated root dentin was also prepared with a carbide bur. Then the root dentin was roughened with a diamond bur followed by etching with 37 % phosphoric acid. There are very few dentin tubules obliterated showing the smear layer produced by the diamond bur yielding a more receptive substrate for acid conditioning (Gomes et al. 2012)

7.3 Chemical Preparation During Endodontic Treatment

The most frequent failure mode of fiber post retained restorations is post debonding (Weston et al. 2007; Cagidiaco et al. 2008; Dietschi et al. 2008). Considering that posts are passively retained into the root canal, the effectiveness of the adhesive bonding plays a relevant role in the overall clinical performance of the restorations. This highlights the importance of knowing the confounding factors that may preclude a strong adhesion between the adhesive cement and the root canal dentin. Some of the irrigants used during endodontic treatment may have a negative impact on root dentin bonding.

7.3.1 Sodium Hypochlorite and Other Oxidizing Solutions

Some solutions routinely used for endodontic irrigation have been reported to play a negative role on the bond strengths of adhesive materials to root canal dentin. NaOCl is an ideal endodontic irrigant widely used in endodontic treatments; however, it may inhibit the polymerization of resin-based materials due to its strong oxidizing property. NaOCl leaves a dentin surface characterized by an oxygen-rich layer that can significantly reduce bond strength (Nikaido et al. 1999; Saleh and Ettman 1999; Perdigao et al. 2000; Morris et al. 2001; Ari et al. 2003; Erdemir et al. 2004; Ozturk and Ozer 2004; Marques et al. 2014).

Not surprisingly, other oxidizing materials that are applied to dentin during endodontic procedures such as *RC-prep*, which is a urea peroxide-based product, leave behind an oxygen-rich surface that also inhibits bonding (Nikaido et al. 1999; Morris et al. 2001; Erdemir et al. 2004). This reduction in bond strength can be reversed by the application of either 10 % ascorbic acid or 10 % sodium ascorbate for at least 1 min (Morris et al. 2001; Weston et al. 2007).

The negative impact of NaOCl on bonding is also evident when resin-based endodontic sealers are used (Rocha et al. 2012; Vilanova et al. 2012) for obturation of the instrumented root canals. Reduced bond strengths were observed between the resin-based sealers and the root canals when sodium hypochlorite was used as an irrigant solution.

7.3.2 EDTA

The combination of *EDTA* and NaOCl is commonly used for endodontic irrigation to achieve demineralization and deproteinization. However, the use of EDTA for longer than 1 min in conjunction with NaOCl creates an erosive dentin surface because of excessive demineralization (Calt and Serper 2002), which makes it difficult to create a strong adhesive interface with a dentin bonding system, especially when using self-etch adhesives (Hayashi et al. 2005). Therefore, from a clinical perspective, prolonged endodontic irrigation with EDTA should be avoided.

7.3.3 Chlorhexidine Digluconate

Chlorhexidine gluconate is an adjunct irrigant during endodontic treatment due to its bactericidal effect. This solution does not jeopardize the bonding of resins to the root dentin (Erdemir et al. 2004), which is advantageous for resin bonding to the root canals. However, as it does not fulfill all the requisites of an endodontic irrigation solution, it cannot replace NaOCl and EDTA solutions. Additionally, as described in the next chapter, chlorhexidine may produce adhesive interfaces less prone to degradation when applied on demineralized dentin before adhesive application (Cecchin et al. 2011, 2014; Martinho et al. 2015).

7.3.4 Calcium Hydroxide

Calcium hydroxide ($CaOH_2$) paste is sometimes used as medication in the root canal for its antimicrobial properties between endodontic sessions. It has been reported that $CaOH_2$ might interfere with bonding of luting cements by acting as a physical barrier (Lee et al. 2014). This can be attributed to the fact that its complete removal is hardly accomplished (Lambrianidis et al. 1999; Maalouf et al. 2013). As reported by Breschi et al. (2009), $CaOH_2$ may also neutralize the self-etching/primer solutions of self-etch adhesives due to its high pH; however, this issue warrants further investigation.

7.3.5 Endodontic Sealers

Although this topic has raised some controversy among different authors, some investigators have reported that the type of endodontic sealer may influence the adhesion between fiber posts and root dentin. It has been demonstrated that post retention is lower in filled canals when compared with non-filled canals, regardless of the type of endodontic sealer (Hagge et al. 2002). This fact highlights the importance of using a root canal sealer when performing in vitro studies to evaluate the bond strength of fiber posts to root dentin.

Some authors observed a loss of retention when *eugenol-based sealers* were used before post luting with resin cements (Tjan and Nemetz 1992; Burns et al. 2000; Alfredo et al. 2006; Aleisa et al. 2012; AlEisa et al. 2013). As other phenolic compounds, eugenol is a radical scavenger that inhibits the polymerization of resin-based materials. However, other studies found no significant difference when comparing eugenol- and *non-eugenol-containing* root canal sealers in terms of post retention when using resin cements (Mannocci et al. 2001; Hagge et al. 2002; Kurtz et al. 2003; Davis and O'Connell 2007).

This controversy from different studies may be attributed to the time elapsed between endodontic obturation and fiber post cementation. For instance, Menezes et al. (2008) evaluated the bond strength of fiber posts to root dentin when post cementation was performed immediately or after 7 days. When the authors used an eugenol-based sealer, the bond strengths were lower when post cementation was performed immediately relative to the bond strength when post cementation was performed after 7 days. Another possible explanation is the amount of dentin removed during the preparation of the post space. The removal of more eugenol-contaminated dentin from root canals treated with eugenol-containing sealer for placing larger diameter posts may increase the post retention (Izadi et al. 2013).

Better retention of fiber post is achieved when resin-based sealers are used compared with fiber posts cemented on root canals previously obturated with eugenol-containing endodontic sealers. The similar chemistry of luting cements and resin sealers and the lack of contamination with eugenol are responsible for this improved bonding (Aleisa et al. 2012; AlEisa et al. 2013).

The clinical indication emerging from several laboratory studies is to refrain from luting the post immediately after root canal obturation. Additionally, the diameter post space should be slightly enlarged. This latter approach, however, may have to be carefully evaluated by the clinician to avoid decrease in fracture resistance of the tooth and root perforations.

Studies have also shown that 3-step ER adhesives result in improved bonding to eugenol-contaminated dentin surfaces as acid etching can remove a great amount of the eugenol-contaminated smear layer (Peutzfeldt and Asmussen 1999; Wolanek et al. 2001). Self-etch adhesive systems should be avoided as they incorporate the eugenol-rich smear layer into the hybrid layer rather than removing it.

7.4 Incompatibility Between Adhesives and Cements

Currently different types of adhesive systems are available. In addition to the full versions of etch-and-rinse [ER] (3-step ER) and self-etch systems [SE] (2-step SE), simplified versions (2-step ER and 1-step SE) are available, which are very popular among clinicians due to their user-friendliness.

However, studies have shown that there is an incompatibility between simplified adhesives (i.e., 2-step ER and 1-step SE adhesives) and chemical- and dual-cured composite resin-based materials (Sanares et al. 2001; Cheong et al. 2003; Tay et al. 2003a, 2004a, b). This is not observed for the full versions of ER (Cheong et al. 2003; Tay et al. 2003b) and SE adhesives (Tay et al. 2002), which is likely due to the presence of an extra hydrophobic resin layer. This incompatibility can be attributed to the acidity of the adhesives (*chemical incompatibility*) (Sanares et al. 2001; Suh et al. 2003) or to the high water permeability of the adhesive layer produced by simplified adhesives, which pull water from the underlying dentin and precludes the close contact of the adhesive and the composite resin (*physical incompatibility*) (Tay et al. 2003a) (Fig. 7.2).

In the chemical incompatibility, an adverse chemical interaction between suboptimally polymerized acidic resin monomers from the oxygen-inhibited layer and the basic tertiary amine catalyst in the chemical or dual-cure composite was thought to be responsible for the observed incompatibility (Sanares et al. 2001). Although this phenomenon was firstly described for chemically and dual-cure composites, some studies have also reported that the same may occur with light-cured composites when used in delayed activation techniques (Tay et al. 2001, 2003b) for the same reason described earlier.

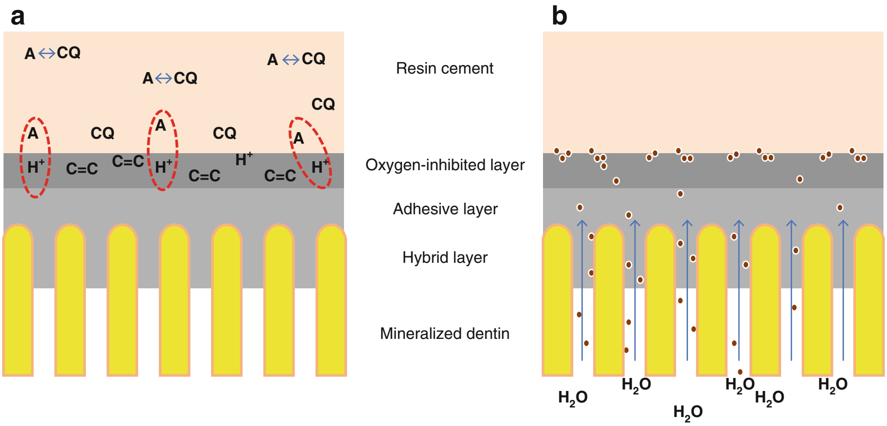

Fig. 7.2 Schematic illustration showing the chemical (**a**) and the physical incompatibilities (**b**) between acidic adhesives and resin cements. In (**a**) the protons (*H*) from acid monomers within the oxygen-inhibited layer compete with camphorquinone (*CQ*) for chemical interaction with the tertiary amines (*A*). This reduces the amount of free radicals to initiate the polymerization reaction. In (**b**), depiction of the easy passage of water from the underlying dentin through the permeable adhesive layer. This water accumulates at the adhesive interface, precluding a tight interfacial bonding with the resin cement

Regarding the physical incompatibility, the presence of an oxygen-inhibited layer creates a hypertonic environment that osmotically draws fluid from the bonded hydrated dentin through the permeable adhesive layer (Tay et al. 2003a, 2004b). As simplified adhesives lack a solvent-free resin coating, water accumulates within the adhesive and also on the adhesive interface, known as water trees (Tay and Pashley 2003). This precludes a good contact with the restorative or luting material.

7.5 Insufficient Light Intensity During Polymerization

The light activation of dental materials within the root canals is a very difficult task, as light does not fully penetrate the length of the post space (Wu et al. 2009; Ho et al. 2011; Moazzami et al. 2012). Light transmission through fiber posts or even without fiber post exponentially reduces as the depth in the root canal increases (Goracci et al. 2008; Wu et al. 2009; Ho et al. 2011; Moazzami et al. 2012) (Fig. 7.3), making the achievement of attaining high bond strength throughout an entire root canal difficult. This explains why several studies reported inferior bonding performance in apical areas when using light-cured adhesives (Bouillaguet et al. 2003; Goracci et al. 2004; Akgungor and Akkayan 2006; Aksornmuang et al. 2007; Mallmann et al. 2007).

The limitation in the distance of light penetration results in a low degree of conversion of polymerizable dimethacrylate resin monomers. When the distance from the light source to the irradiation surface was increased, the degree of conversion of resin monomers decreased (Le Bell et al. 2003; Hayashi and Ebisu 2008).

It was recently demonstrated that even in the presence of translucent posts, the amount of light reaching the apical third of the root space might not be sufficient to

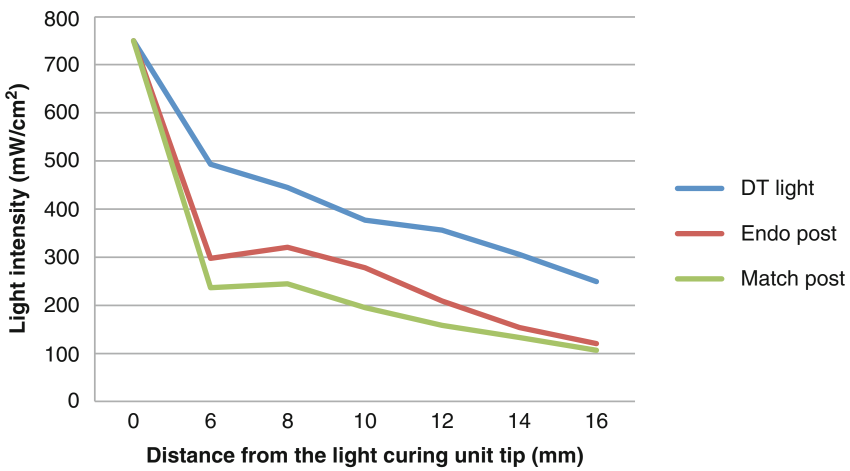

Fig. 7.3 Light attenuation through three different fiberglass post systems. The 0 mm represents the incisal region of a central incisor where the light intensity is 100 % (Adapted from Moazzami et al. (2012))

effectively cure the cement at that level (Goracci et al. 2008). In the same investigation it was demonstrated that light transmission was not only prevented in carbon fiber posts but also significantly reduced in glassfiber posts marketed as being translucent, to the point that resin cement curing would be affected (Goracci et al. 2008; Ho et al. 2011).

7.6 Operator Experience

Bonding fiber posts to root canals is technically complicated. The quality of complex restorative protocols is highly susceptible to the operator's experience. It has indeed been proven that there is variability in the results of adhesive procedures on coronal dentin that results from the operator experience (Sano et al. 1998; Miyazaki et al. 2000).

More recently the same was observed for fiber post cementation procedures. When full or simplified versions of ER adhesives were used to bond fiber posts to the root canals, reduced bond strength was observed for less experienced clinicians (Gomes et al. 2013). On the other hand, the role of operator was not significant when a self-adhesive cement was used.

Failure to follow the manufacturers' recommendations and little knowledge about the confounding factors that affect root dentin bonding might well explain the reduced bonding of ER adhesives when applied by less experienced clinicians. The reduction in clinical steps as well as no need to keep the dentin substrate moist prior to material application might explain why self-adhesive cement was not sensitive to the operator's skill. For less experienced operators, reducing the steps of the bonding procedure may be an important factor in obtaining a more reliable and stronger bond between resin and root dentin.

7.7 Cavity Configuration (C-Factor)

During polymerization of methacrylate-based materials, resin monomers get closer to one another, reducing the intermolecular spaces between them. This results in shrinkage stress that is sufficient to cause material debonding from root dentin. From a clinical standpoint, this stress leads to reduction of the post retention, gap formation, and potential for bacterial leakage at the adhesive interface.

Feilzer et al. (1987) reported that the shrinkage stress is related to the cavity configuration factor (C-factor), defined as the ratio of bonded to unbonded surface areas of the restoration. The higher the bonded area, the highest the extent of shrinkage stress and the damage to mechanical properties of the resin cement (Jongsma et al. 2012). Within the root canal, the cavity geometry is unfavorable and considered the worst scenario in achieving gap-free interfaces, since there are not enough unbounded surface areas for stress relief.

In comparative terms, while coronal restorations can have C-factors varying from 1 to 5, the estimated C-factor in post spaces may exceed 200 (Bouillaguet et al.

Fig. 7.4 Over instrumented root canal showing a mismatch between the root canal and the thickest glassfiber post available. To minimize the deleterious effect of polymerization shrinkage stress from the excessive volume of resin cement, some clinical alternatives such as the use of direct and indirect glassfiber posts may be employed

2003; Breschi et al. 2009). A way to minimize this unfavorable scenario is reducing the thickness of the adhesive resin cement layer inside a tight constrained cavity (root canal) that does not allow for stress relief by flow. The use of techniques that decrease the volume of material in the root canal (such as direct or indirect anatomic posts) may reduce the undesirable effects of polymerization shrinkage and yield higher bond strengths of fiber posts to root canal. It may also reduce the gap formation at the dentin-cement interface (Gomes et al. 2014).

Reducing the volume of resin cement may be difficult to achieve due to the shape mismatch between the circular fiber posts and the oval shape of many root canals or over instrumented canals (Fig. 7.4). Relining the prefabricated post with a composite resin outside the root canal before the cementation procedure may be useful in clinical practice to minimize the undesirable consequences of the constrained root canal cavity into the bonded interface (Faria-e-Silva et al. 2009; Macedo et al. 2010; Gomes et al. 2014).

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Methods for Increasing the Longevity of Adhesion to Root Canal Dentin

8

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Abstract

All bonding protocols undergo degradation over time, and this may be one of the reasons why fiberglass post is prone to debonding during clinical service. The understanding of the mechanisms behind such degradation is crucial for clinicians to implement alternatives to minimize the degradation process and prolong the lifetime of post-retained restoration. This chapter will describe the degradation mechanisms that adhesive interfaces created in the root canal are prone to and also discuss clinical alternatives that can be incorporated into the clinical protocol to maximize the bonding longevity.

8.1 Introduction

Most clinical failures involving endodontically treated teeth restored with fiber post occur through debonding (Aksornmuang et al. 2004). Overall, clinical studies have generally reported that debonding occurs sporadically during the restoration lifetime with no noticeable tendency for immediate failure (Rasimick et al. 2010). The possible causes are the anatomical and histological features of root dentin, including the dentin tubule orientation (Mannocci et al. 2004), the nonuniform dentin hybridization on this substrate (Vichi et al. 2002), and many other factors described in other chapters of this book. In spite of these limitations, there is some consensus that high and durable bond strengths of fiber posts to root canal are crucial to ensure long-term success of any restorative procedure that relies on the post cementation into the root canal, as bonding between post and root dentin has been found to

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decrease microleakage (Bachicha et al. 1998; Reid et al. 2003) and improve retention (Junge et al. 1998; Hedlund et al. 2003; Schwartz and Robbins 2004), in comparison with conventional cements.

The durability of bonding to root canal is closely related to the intrinsic susceptibility of the hybrid layer (HL) components to degradation (Van Meerbeek et al. 2003; Breschi et al. 2008). Although the exact mechanism responsible for HL degradation is not fully understood (Breschi et al. 2008; Vaidyanathan and Vaidyanathan 2009), the intrinsic resistance to degradation will depend mostly upon full impregnation of resin monomers into demineralized root dentin along with optimal monomer conversion to polymer, to provide long-term post retention in the root canal (Perdigao et al. 2013; Reis et al. 2013). Therefore, it is crucial for clinicians to understand the mechanisms responsible for HL degradation at the adhesive interface created between adhesive materials and root dentin. This chapter describes the mechanisms involved in the degradation within the HL created when bonding agents are applied to root canal prior to fiber post cementation and then some variations in the clinical protocol that may maximize the bonding longevity.

8.2 Factors Involved in the Aging of Adhesion to Root Canal Dentin

As the HL is created by a combination of dentin organic matrix, residual hydroxyapatite crystallites, resin monomers, and solvents, aging may affect each of the individual components or may be due to synergistic combinations of degradation phenomena occurring within the HL (Breschi et al. 2008). Thus, for didactic reasons, the degradation of the main components of the HL will be discussed separately.

8.2.1 Degradation of the Polymer Network

Most commercial bonding agents have *hydrolytically susceptible groups*, such as ester, urethane, hydroxyl, carboxyl, and phosphate groups in their structures; therefore, water has a detrimental influence on the mechanical properties of these components (Ferracane 2006). Indeed, because of their composition, these products are highly susceptible to water sorption to a damaging extent (Malacarne et al. 2006; Reis et al. 2007b). As a consequence, such a hydrophilic nature of bonding resins easily induces long-term water absorption caused by the replacement of hydrophilic resin monomers by water even after curing, leading to hydrolytic degradation (Tay et al. 2004; Malacarne et al. 2006). In other words, the hydrophilic layer of bonding agents created within the HL may induce water sorption and uptake, which plasticize and weaken the polymer network (Shono et al. 1999; Tanaka et al. 1999; Abdalla and Feilzer 2008), resulting in a decreasing bond strength over time (De Munck et al. 2003; Abdalla and Feilzer 2008).

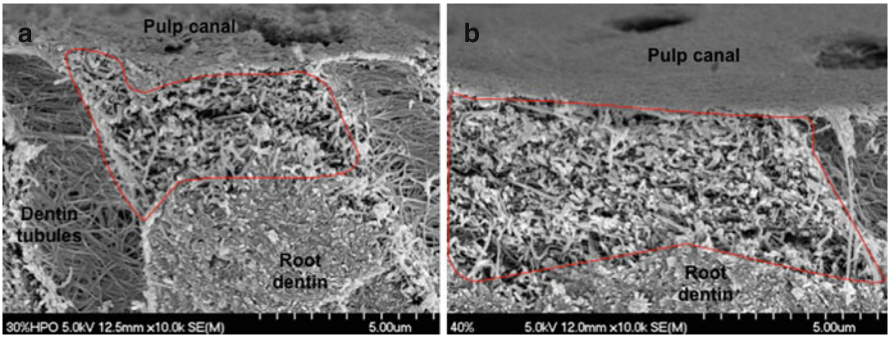

Fig. 8.1 Scanning electron microscopy (SEM) micrograph of dentin etched with 30 % (in **a**) and 40 % (in **b**) phosphoric acid for 15 s. Observe the area of demineralized dentin (*red*)

8.2.1.1 Etch-and-Rinse (ER) Adhesive Systems

The clinical scenario of polymer degradation becomes more critical in the wet-bonding technique, as water plays a crucial role to ensure proper monomer infiltration in to the demineralized dentin. In this adhesion strategy, acid etching demineralizes the dentin surface, exposing a thin collagen network to provide space for resin infiltration. The acid is rinsed off with water, which must remain to some extension to preserve the collagen interfibrillar spaces and then allow the resin monomers to infiltrate the demineralized dentin (Fig. 8.1) (Kanca 1992, 1996). For this reason, organic solvents are added to the bonding resin formulations to allow easier and faster evaporation of both solvent and remaining water (Carvalho et al. 2003; Yiu et al. 2005b; Reis et al. 2013).

However, although most dental adhesive manufacturers recommend protocols for solvent evaporation, complete solvent elimination is difficult to accomplish, mainly when the solvent is added to highly hydrophilic adhesive blends (Pashley et al. 1998; Carvalho et al. 2003; Yiu et al. 2005b). As a consequence, the *presence of residual water and solvents* may further prevent the reactive pendant species to approximate, making cross-linking reaction inside the HL more difficult (Figs. 8.2 and 8.3) (Paul et al. 1999; Ye et al. 2007; Loguercio et al. 2009).

Thus, instead of achieving optimal macromolecular packing density, the polymer network may have its free space greatly increased to a level directly related to the amount of remaining organic solvent during polymerization. Once the extent and rate of water uptake is dependent upon the chemistry of adhesive systems (Ito et al. 2005a; Malacarne et al. 2006; Malacarne-Zanon et al. 2009; Reis et al. 2013), the poorly polymerized resin will eventually expedite water sorption and compromise the long-term integrity of adhesive–dentin interface (Reis et al. 2013).

Although the bonding mechanisms on root dentin are similar to coronal dentin (Mannocci et al. 1999; Ferrari et al. 2000; Breschi et al. 2009), polymer degradation in root dentin is more problematic than that observed in any other region. As previously mentioned, because of root canal anatomy, removal of phosphoric acid and moisture control when ER adhesive systems are used cannot be successfully

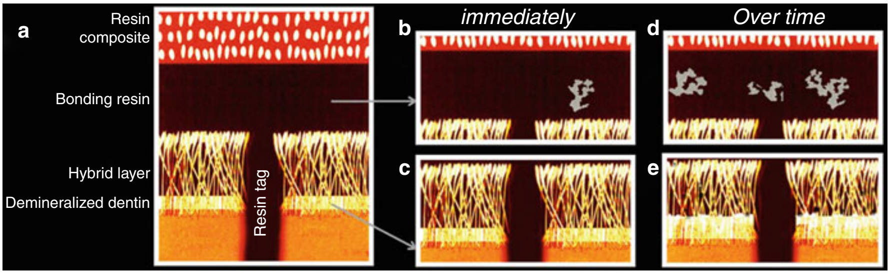

Fig. 8.2 Schematic drawing representing the sequence of resin–dentin bonding degradation over time (Adapted from Perdigao et al. (2013)). (**a**) Resin–dentin bonding interface. (**b**) The presence of silver nitrate deposits (in *gray*) in the adhesive layer soon after bonding indicates the presence of retained water/solvent, as well as areas of inadequate polymerization. (**c**) Areas of denuded collagen fibers, incompletely infiltrated by resin monomers, are present at the base of the hybrid layer. These collagen fibers are prone to degradation by host-derived proteinases. (**d**) Degradation continues over time because of water sorption. The polymer swelling leads to the release of oligomers and residual monomers, which are not cross-linked to the main polymer chains. This can be identified by an increase in the number of silver nitrate deposits in the adhesive layer. (**e**) The area of incomplete collagen infiltration also increases with time (Reprinted with permission)

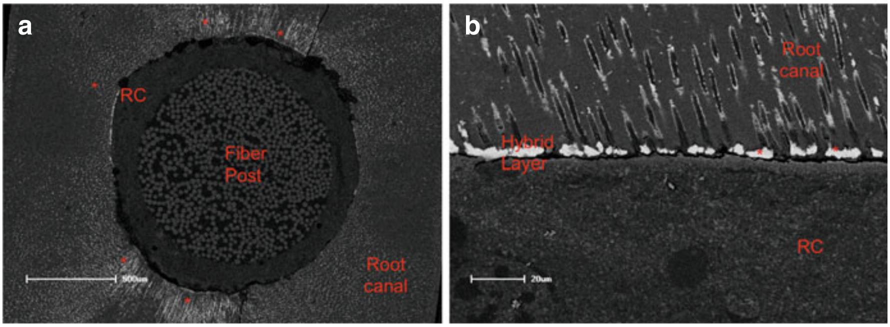

Fig. 8.3 SEM of the apical third of the post cemented as simplified ER adhesive associated to a dual-cure resin cement (RC). (**a**) Occlusal view of the interface between post and root canal. Observe the higher amount of nanoleakage around the interface between adhesive/resin cement interface and root canal (*red asterisks*). In (**b**), in higher magnification, nanoleakage inside the hybrid layer

accomplished (Breschi et al. 2009). As a consequence, higher amount of residual water remains on the demineralized dentin, mainly in the middle and cervical thirds of the root (Thitthaweerat et al. 2013).

Additionally, *attenuation of light emitted by the light-curing unit* due to root anatomy may result in even poorer monomer conversion of bonding agent and resin cement layers at the middle and cervical thirds (Roberts et al. 2004; Faria e Silva et al. 2007). The resulting poor polymerization added to the higher content of remaining residual water/solvent will eventually turn the adhesive interface at the middle and apical thirds more prone to hydrolytic degradation than that from the cervical third, leading to lower short- and long-term bond strengths as reported in the literature (Foxton et al. 2003; Monticelli et al. 2006).

8.2.1.2 Self-Etching (SE) Adhesive Systems

The use of SE adhesive systems along with resin cements to bond posts to root canals became an option to overcome the limitations imposed by the technique-sensitive ER adhesion strategy. In contrast to ER adhesive systems, SE adhesives systems have acidic monomers capable of partially involving original smear layer in the HL (Watanabe et al. 1994; Nakabayashi and Saimi 1996). In other words, the acidic monomers penetrate into the smear layer, smear plug, and underlying intact dentin. Therefore, the HL created by SE systems is a combined structure of adhesive resin, collagen fibrils, and minerals. For this reason, SE adhesive systems do not require previous phosphoric acid etching or wet-bonding technique (Watanabe et al. 1994), so they allow clinicians to control the application technique to root canals better than do conventional ER adhesive systems.

However, due to the *high hydrophilic monomer and solvent contents*, one-step SE adhesive systems have a more hydrophilic nature, so they exhibit higher water sorption rate and hydrolytic degradation than do ER systems (Breschi et al. 2008; Reis et al. 2013). This leads to the creation of HLs that are permeable not only to water from oral environment but also to fluids flowing from the dentinal tubules (Chersoni et al. 2004; Tay et al. 2004; Hashimoto et al. 2004b). In addition, as dual-cured resin cements are usually required when cementing posts to root canals, a *chemical incompatibility between acidic monomers from simplified self-adhesive systems and self-curing components of dual-cured resin cements* has been reported (Sanares et al. 2001; Tay et al. 2003b; Arrais et al. 2009).

When light emitted by light-curing units is severely attenuated at the apical third due to root anatomy and the polymerization of resin cement solely relies on self-curing components, the interaction between acidic monomers from self-etching adhesive systems or even from simplified two-step ER systems and resin cement layer will not allow the cement polymerization to occur at the apical third (Sanares et al. 2001; Arrais et al. 2009). This incompatibility between SE adhesive systems and dual-cured resin cements results in higher permeability and hydrolytic degradation of the adhesive layer (Tay et al. 2003b).

8.2.1.3 Self-Adhesive Resin Cements

Recently, following the trend toward simplification, manufacturers have developed resin cements that do not require previous application of bonding agents, the so-called self-adhesive resin cements. These cements have acid-functionalized monomers, such as with 4-methacryloxyethyl trimellitic anhydride (4-META) and pyromellitic glycerol dimethacrylate (PMGDM), or phosphoric acid groups, as with 2-methacryloxyethyl phenyl hydrogen phosphate (phenyl-P), 10-methacryloyloxydecyl dihydrogen phosphate (MDP), bis(2-methacryloxyethyl) acid phosphate (BMP), and dipentaerythritol pentaacrylate monophosphate (Penta-P), in their composition to achieve demineralization and bonding to the tooth surface (Ferracane et al. 2011).

When self-adhesive resin cements are mixed, the acidic monomers create a pH ranging between 1.5 and 3 to gently demineralize dentin and enamel surfaces (Ferracane et al. 2011). The acidic groups bind with calcium in the hydroxyapatite to form a stabilizing ionic attachment between the methacrylate network and dentin. Ions released from the acid-soluble filler neutralize the remaining acidic groups to create a chelate-reinforced three-dimensional methacrylate network. For the first minutes, the cements are fairly hydrophilic, which allows proper wetting and adaptation to the tooth surface.

As the acid functionality is consumed through reaction with calcium from hydroxyapatite and a variety of metal oxides from the cement ion-leachable fillers, these materials become more hydrophobic (Ferracane et al. 2011), so these products would be less prone to hydrolytic degradation than simplified ER and SE adhesive systems. Although short-term results have shown better results in terms of bond strength promoted by these cements in comparison to those obtained with conventional dual-cured resin cements (Sarkis-Onofre et al. 2014), recent long-term studies have shown a drop in bond strength of posts cemented with self-adhesive resin cements over time (Mazzoni et al. 2009a; Marchesi et al. 2013). In general, researchers have attributed this decrease in bond strength to the plasticization of the polymer matrix to water, as these cements may not all shift to neutrality and hydrophobicity as expected (Mazzoni et al. 2009a; Goracci and Ferrari 2011; Marchesi et al. 2013).

Overall, hydrolytic degradation may be considered the main mechanism responsible for the decrease in bond strength over time when adhesive systems are applied to in vivo coronal dentin (Breschi et al. 2008, 2009; Perdigao et al. 2013; Reis et al. 2013). In that scenario, *fluid movement through dentin tubules toward the adhesive interface*, along with residual water from wet-bonding technique when ER systems are used, or water/solvent present in the bonding agents, is responsible for the hydrolytic degradation within the HL (Breschi et al. 2008, 2009; Perdigao et al. 2013; Reis et al. 2013). Nonetheless, no fluid movement through dentin tubules is observed in the intra-radicular dentin. Moreover, direct intraoral exposure of the post-composite interface is usually avoided by immediately restoring a tooth with a direct composite restoration or a crown, which means that water is not in direct contact with the bonding/luting/post system (Vano et al. 2006; Ferrari et al. 2008).

Indeed, only in the worst-case scenario, when the coronal restoration fails to seal the margins and oral fluids reach the bonding/luting/post, faster polymer degradation may be expected. For this reason, despite the evidence that water does have important effects on polymer degradation of ER, SE, or even self-adhesive resin cements, water from the dentin tubules should not be regarded as the main factor related to aging of the adhesive interface in the intra-radicular dentin (Breschi et al. 2009).

8.2.2 Degradation of Collagen Fibrils

After endodontic treatment followed by the use of calibrated burs to prepare the post space, intra-radicular and coronal dentin present similar composition and structure (Ferrari et al. 2000). This substrate is a nonhomogeneous tissue characterized by the presence of tubules extending from the pulp to the root periphery (Ferrari et al. 2000), so intertubular and peritubular dentin are present. For these reasons, degradation of collagen fibrils within the HL at the intra-radicular dentin may be similar to that observed in the coronal dentin (Breschi et al. 2009).

Recently, it has been reported that the enzymes involved in the breakdown of the collagen matrices during the pathogenesis of dentin caries (Tjaderhane et al. 1998;

van Strijp et al. 2003) and periodontal disease (Lee et al. 1995) have potential and relevant implications in the degradation of resin–dentin-bonded interfaces (Pashley et al. 2004). More specifically, dentin collagen fibrils contain inactive proforms of proteolytic enzymes called *matrix metalloproteinases (MMPs)*, secreted as proenzymes (zymogens), that were identified in both odontoblasts and mineralized or demineralized human dentin (Bourd-Boittin et al. 2005; Mazzoni et al. 2007; Sulkala et al. 2007). Several MMPs have been identified in mineralized human dentin, in an inactive state – MMP-8 collagenase (Sulkala et al. 2007), MMP-2 and MMP-9 gelatinases (Mazzoni et al. 2007, 2009b), and MMP-20 enamelysin (Sulkala et al. 2002). Although MMP-2 and MMP-9 are considered as gelatinases, other researchers have described collagenolytic activity associated with these two MMPs (Aimes and Quigley 1995; Garnero et al. 2003).

MMPs can be activated by proteinases or by some chemical agents, including reactive oxygen species. In other words, such enzymes can be activated when exposed to acidic agents during adhesive bonding procedures. If these matrix-bound, activated MMPs are not fully infiltrated with adhesive resin, they may be able to slowly degrade the collagen fibrils inside the resin–dentin-bonded interface (Carrilho et al. 2007). Therefore, the degradation of collagen fibrils is dependent upon the lack of proper collagen fibril encapsulation by resin monomers and MMP activation.

For instance, the HL thickness and the resin tag density decrease from the coronal to the apical third of a root (Ferrari et al. 2000). In addition, other authors noticed that the penetration of adhesives inside radicular dentin proved to be complete in only one-third of extracted teeth in the apical third and in two-thirds of the samples in the middle and coronal thirds (Mannocci et al. 2003).

Regarding the dentin adhesives, when ER bonding agents are applied to a previously acid-etched dentin, a decreasing gradient of resin monomer diffusion within the acid-etched dentin (Wang and Spencer 2002) results in incompletely infiltrated areas along the bottom of the HL that contain denuded collagen fibrils (Wang and Spencer 2002; Hashimoto et al. 2003; Spencer et al. 2004) as a consequence of previous acid etching. Therefore, the discrepancy between the depth of the exposed collagen layer without surrounding minerals and resin infiltration creates an exposed demineralized dentin zone under the HL (Figs. 8.2 and 8.3) (Spencer and Swafford 1999; Pioch et al. 2001). Curiously, intense MMP-2 and MMP-9 activities were detected at the basal part of the HL (De Munck et al. 2009; Breschi et al. 2010).

Conversely, when SE adhesive systems are applied to dentin, the smear layer is completely or partially incorporated into the bonding interface, providing simultaneous demineralization and infiltration during the application of the acidic monomer. For this reason, researchers now believe that simultaneous demineralization and monomer infiltration might overcome the shortcomings related to the presence of an exposed collagen network within the bonding interface created by phosphoric acid in ER adhesives. However, *incomplete infiltration* has also been observed with SE adhesives based on the presence of nanoleakage within the HL (Tay et al. 2002; Tay and Pashley 2003) as a result of nanometric-sized channels for water impregnation into bonding interfaces (water–trees). In both scenarios, when dentin MMPs are exposed and activated by SE or ER adhesive systems (Mazzoni et al. 2006), these enzymes degrade type I collagen (Carrilho et al. 2009).

As previously described in this chapter, regardless of the bonding strategy when using simplified adhesives (two-step ER and one-step SE adhesive systems), by combining hydrophilic and ionic resin monomers into the adhesive solution, the bonded interface would benefit from a non-solvated hydrophobic resin coating. This leads to the creation of HLs that are permeable not only to water from oral environment but also to water flow coming from the dentinal tubules (Chersoni et al. 2004; Tay et al. 2004; Hashimoto et al. 2004b). For this reason, the adhesive interfaces formed with simplified adhesives are considered semipermeable membranes (Tay et al. 2002; Carvalho et al. 2003; Tay and Pashley 2003). The use of a non-solvated hydrophobic resin coating will be discussed in this chapter.

As a consequence, the elution of resin from hydrolytically unstable polymers within the HL results in further exposure of collagen fibrils (Perdigao et al. 2013). Therefore, in root dentin, under the condition of a breach of the coronal seal, or in the case of the water-rich simplified SE adhesives, water may promptly permeate these HLs, allowing the activated MMPs to exert their hydrolytic function upon the collagen fibrils. In addition, recent studies have shown that by-products of both root canal sealers (Huang et al. 2008) and bacteria related to endodontic infections (Itoh et al. 2009) were able to activate at least proMMP-2 and proMMP-9, two of the dentinal MMPs that are thought to be involved with the degradation of collagen fibrils within resin-bonded dentin interfaces (Mazzoni et al. 2007, 2009b). Within this context, this scenario becomes more critical in root canals as naturally occurring tissue inhibitors of matrix metalloproteinases (TIMPs) that are normally present in extracellular matrices for regulating MMP activities (Reynolds and Meikle 1997; Malemud 2006) are depleted after the extirpation of the pulpal tissues and filling of the root canals with synthetic materials.

In addition to MMPs, different *cysteine cathepsins* are also expressed in human pulp tissue or odontoblasts and present in human dentin (Tersariol et al. 2010). Cathepsins, a family of lysosomal papain-like cysteine proteases, can degrade most of the extracellular matrix proteins, such as collagen, laminin, and proteoglycans (Turk et al. 1997; Dickinson 2002), and their activity can be found in both sound and carious human dentin (Tersariol et al. 2010; Nascimento et al. 2011). As cathepsins are autoactivated in slightly acidic environments (Dickinson 2002), some authors recently noticed that these endogenous enzymes can be activated by low-pH SE adhesive systems (Zhang et al. 2014). According to these authors, the acidic monomers can demineralize the dentin matrix and expose and activate these enzymes. Therefore, along with MMPs, cathepsins might also contribute to the endogenous proteolytic activity of dentin, resulting in collagen degradation within the HL, which may influence dentin bond durability (Liu et al. 2011; Tjaderhane et al. 2013b).

In conclusion, in order to achieve long-term post bonding to root canals, care must be taken to ensure that exposed collagen fibrils are fully enveloped by resin monomers after ER or SE adhesive systems are applied to avoid collagen exposure to such enzymes. In addition, remaining water and residual solvent should be removed as much as possible, and the bonding agents must be properly exposed to light emitted by the light-curing unit so optimal polymerization can be obtained. Due to the limitations imposed by the root canal anatomy, other clinical approaches may be required to fulfill these conditions.

8.3 How to Improve the Resin–Dentin Bond Stability

Based on the foregoing discussion, one may assume that the quality of the adhesive interface will rely on the use of techniques that favor the formation of a fully resin-impregnated HL, with proper enveloping of the exposed collagen fibrils with a highly cross-linked polymer. Several studies have focused on the effects of modified standard clinical protocols to obtain adhesive interfaces with higher resistance to degradation. Unfortunately, most of the in vitro studies were conducted on coronal dentin and most of them still lack evaluation on root dentin. On the other hand, considering the similar composition and structure of coronal and root dentin, the protocols with promising results on coronal dentin will probably improve the immediate and long-term adhesion of fiber posts to root dentin.

In summary, these clinical protocols focus on (1) improving resin impregnation into mineralized and demineralized dentin substrates, (2) improving the strength of the polymer formed by the adhesive systems, and (3) improving the resistance of collagen fibrils to enzymatic degradation. Some clinical approaches may improve bond durability using two or even three of these mechanisms; however, for didactic reasons, they will be classified into one of these approaches.

8.3.1 Improving Resin Impregnation into Mineralized and Demineralized Dentin Substrates

8.3.1.1 Preparation of Root Canal with Diamond Bur

The use of a phosphoric acid after post space preparation with a carbide bur resulted in discontinuous areas of deep intertubular demineralization alternating with areas characterized by open tubules and other areas covered by debris, smear layer, and gutta-percha and/or sealer remnants. This makes the chemical dissolution of this layer rather difficult (Serafino et al. 2004; Breschi et al. 2009). On the other hand, when the preparation of the root canal was performed with a diamond bur, the same etching procedure was capable of removing the smear layer more efficiently, ensuing more open dentin tubules and less smear layer remnants (Gomes et al. 2012).

As no manufacturer provides diamond burs for root wall preparations, clinicians may abrade the root walls with a diamond bur after the use of the manufacturer-provided carbide bur. In this case, the use of a diamond bur with similar diameter will replace the acid-resistant smear layer produced by the carbide bur with a smear layer more susceptible to phosphoric acid dissolution.

8.3.1.2 Use of a Liquid Acid Etchant

As previously reported, dissolution of the smear layer remnants using a phosphoric acid gel is not effectively accomplished in the root dentin walls. After endodontic treatment, obturation, and post space preparation, SEM analysis of canal walls along post space shows large areas covered by smear layer, debris, and sealer/gutta-percha remnants not available for adhesive bonding and resin cementation of fiber posts (Serafino et al. 2004).

Etchants with a gel consistency preclude a close interaction between the acid and the dentin substrate. Some recent studies have reported that liquid phosphoric acid applied with an endodontic needle yielded better smear layer removal from the canal wall and higher bond strengths when an ER adhesive system was used, especially if applied actively (Salas et al. 2011; Scotti et al. 2013).

8.3.1.3 Vigorous Adhesive Application

The gentle application of simplified ER systems limits the diffusion of resin monomers (especially those with high molecular weight) into the wet demineralized root dentin. This is attributed to factors such as the difficulty in the management of moisture inside the root canal. If the adhesive is rubbed vigorously, the adhesive solution may be better drawn into the dentin collagen network (Jacobsen and Soderholm 1998; Reis et al. 2007a), increasing solvent diffusion outward and improving the polymer cross-linking inside the HL.

Recently, Cuadros-Sanchez et al. (2014) evaluated three simplified ER adhesives into the root canal when applied as per manufacturers' instructions or with the aid of a sonic device (to simulate vigorous application). The authors reported increased bond strength, higher in situ degree of conversion of the adhesive, and reduced nanoleakage mainly in the apical third for the groups where adhesive was applied with the sonic device.

Promising results were also obtained when this sonic device was used for application of SE adhesives (unpublished data). For SE adhesives, vigorous agitation has an additional advantage – carry fresh acidic resin monomers to the basal part of the demineralized dentin, producing a deeper demineralization and carrying more resin, which, in turn, promotes a better interaction with the smear layer and underlying dentin. In comparison with the manual vigorous application, the use of a sonic device may provide a less sensitive procedure, but it warrants further evaluation.

8.3.1.4 Multiple Coats

It has been demonstrated that the application of multiple coats of simplified ER and SE adhesives to coronal dentin yields higher immediate bond strengths (Hashimoto et al. 2004a; Ito et al. 2005b) and also makes the adhesive interface less prone to degradation over time (Reis et al. 2008). For both types of adhesives (i.e., ER and SE), the application of multiple coats improves the saturation of the HL with resin monomers while favoring solvent evaporation. Additionally, additional layers of unpolymerized comonomers of SE adhesives may improve the etching ability of the adhesive by carrying more acid monomers to the basal part of the HL to replace those that were already buffered by dentin (Camps and Pashley 2000).

The benefits of this approach into the root canal have not been investigated so far but may likely be similar to those of coronal dentin. This protocol, however, should be applied with caution as multiple adhesive coats may also increase the thickness of the adhesive layer, which may in turn affect the post seating inside the post space. The use of paper points to remove the excess of solvent may prevent such undesirable consequences.

8.3.2 Improving the Strength of the Polymer Formed by Adhesive Systems

8.3.2.1 Hydrophobic Resin Coating

One way to counteract the hydrophilicity of simplified adhesives is to place an *additional coating of hydrophobic resin* onto the polymerized simplified adhesive. The use of a hydrophobic coating after the application of simplified SE and ER adhesive systems results in a thicker and more uniform adhesive layer with low concentration of retained water and solvent and significant reduction in the fluid flow rate (King et al. 2005; de Andrade e Silva et al. 2009).

This technique is also capable of eliminating the chemical and physical incompatibility of simplified SE adhesives with chemically cured composites (King et al. 2005; Van Landuyt et al. 2006). Dentin adhesive systems that utilize the separated non-solvated hydrophobic bonding resin (three-step ER and two-step SE) show higher degree of polymerization and less permeability to water (Cadenaro et al. 2005; Breschi et al. 2007).

The application of an extra hydrophobic resin coating over a one-step SE adhesive would convert the simplified adhesive in a more stable two-step SE adhesive. In turn, if the hydrophobic coating is applied over a two-step ER adhesive, this would become a more stable three-step ER adhesive. The simplified adhesive would be further concentrated with more hydrophobic monomers from the additional surface coating (Breschi et al. 2008), as well as shown by Lombardo et al. (2008). Consequently, a more stable resin–dentin interface can be formed over time (Reis et al. 2008). This protocol transforms a simple-layer adhesive into a multilayer one, with the difference that the most hydrophilic simplified adhesive is photoactivated before the application of the most hydrophobic, non-solvated bonding resin.

More densely compacted HLs are produced by reducing the concentration of unreacted monomers between the primed and bonded layers (de Andrade e Silva et al. 2009). This approach, however, should be carried out with caution to avoid the formation of a thick layer of adhesive that would interfere with the post seating inside the post space.

8.3.2.2 Ethanol Wet Bonding

As previously mentioned, simplified ER and SE adhesives are composed of hydrophilic monomers with higher potential for water sorption and degradation. Unfortunately, hydrophobic resins, as neat Bis-GMA/TEGDMA resins, are insoluble in water-saturated dentin. The rationale behind *ethanol wet bonding* (Breschi et al. 2007; Sadek et al. 2008) is to use ethanol to replace water in acid-etched collagen so that hydrophobic resins can infiltrate the demineralized dentin to create hydrophobic HLs.

Hydrophobic resins absorb little water from dentin (Sadek et al. 2008). The application of hydrophobic resins to ethanol-wet dentin may provide resin interfaces with a fivefold reduction in the water sorption rates (Yiu et al. 2004; Ito et al. 2005a; Malacarne et al. 2006). Also, as MMPs become inactive in the absence of water, the replacement of water with an organic solvent, such as ethanol, is also a potential mechanism for extending the longevity of resin–dentin bonds (Tjaderhane et al. 2013a). The ethanol wet bonding technique yielded higher immediate bond strength and lower nanoleakage in root canals (Duan et al. 2011; Pei et al. 2012). Stable bond strengths to intra-radicular dentin were reported after 6- and 12-month in vitro evaluations (Bitter et al. 2014; Ekambaram et al. 2014), although this benefit is not supported by other data (Cecchin et al. 2011).

The ethanol saturation is achieved by using a series of ascending ethanol concentrations, taking approximately 3–4 min, which defies the principles of user-friendliness and technique simplification (Osorio et al. 2010). A recent study, however, showed promising results using simpler protocol: the authors applied a higher concentration of ethanol for 60 s (Sauro et al. 2010). This simplified protocol can be translated to a routine clinical practice without much difficulty.

8.3.2.3 Improved Polymerization Through the Root Canal

Manufacturers of some ER and SE adhesives provide a separate bottle of activator solution containing ternary catalyst that must be mixed with the adhesive before application. However, these materials also depend on light curing to reach a high degree of conversion (Faria-e-Silva et al. 2008).

Similarly, dual-curing resin cements develop better mechanical properties when they are exposed to curing light (Pegoraro et al. 2007; Manso et al. 2011). Therefore, exposure to curing light has been suggested even when dual-cure cements are used (Caughman et al. 2001; Goracci et al. 2008; Breschi et al. 2009; Wu et al. 2009). Thus, to overcome the insufficient light diffusion in the narrow post space, clinicians have been advised to use a high-intensity light-curing unit and/or prolong the irradiation time of adhesive systems/resin cements to improve the adhesion of adhesives/resin cement to root canal dentin (Akgungor and Akkayan 2006; Aksornmuang et al. 2008; Teixeira et al. 2009; Miguel-Almeida et al. 2012).

Extension of the light-curing time was found to be effective to improve the bond strength to root dentin (Aksornmuang et al. 2006). The use of translucent post is not considered a definitive solution, mainly because it did not transmit enough light to the apical third of the root canal (Teixeira et al. 2006; dos Santos Alves Morgan et al. 2008; Goracci et al. 2008). Other options, such as using a LED fiber or a transparent light-guiding attachment to deliver light into the deepest parts of the root canal, might be considered as viable options (Goracci and Ferrari 2011).

8.3.2.4 Oxalate-Containing Desensitizers

One of the drawbacks of using simplified adhesive systems is that they behave as semipermeable adhesive interfaces that allow transudation of fluids from the underlying dentin. Dentin permeability of root dentin can be reduced by applying oxalate-containing desensitizers (Gillam et al. 2001; Tay et al. 2003a; Garcia et al. 2010). Following acid etching, dentin permeability is significantly increased by removal of the smear layer. The sequential application of an oxalate desensitizer and a two-step ER adhesive on acid-etched hydrated dentin reduces convective water fluxes through the dentin. This allows better contact of the resin cement and the adhesive layer, preventing the well-known physical incompatibility between simplified adhesives and resin cements.

Depletion of calcium ions by the use of phosphoric acid on dentin forces the oxalate ions to diffuse further down into the dentinal tubule, until calcium ions are encountered for reaction (Tay et al. 2003a). Oxalic acid (pH 2.3) is acidic enough to etch dentin and liberate sufficient calcium ions to form insoluble calcium oxalate crystals that occlude patent tubules in exposed dentin. This can also limit the osmotically induced water movement during bonding procedures, thus decreasing the amount of water entrapped within these adhesives.

Although this technique manages well the physical incompatibility between adhesive and resin cements, its use is restricted to ER adhesives, as oxalates must be applied on acid-etched dentin. Another disadvantage of the use of oxalate-containing desensitizer is that its use with fluoride-containing adhesives or adhesives with pH lower than 2.8 should be avoided as they would dissolve the oxalate crystals (Yiu et al. 2005a).

8.3.3 Improving the Resistance of Collagen Fibrils to Enzymatic Degradation

8.3.3.1 Chlorhexidine (CHX)

Despite its long-lasting use as a disinfectant and antimicrobial agent in restorative dentistry and endodontics, especially as a final irrigant of root canals (Mohammadi and Abbott 2009; Gomes et al. 2013), only recently has CHX been employed as a protease inhibitor to preserve the HL against degradation through inhibition of MMPs (Pashley et al. 2004) and cysteine cathepsins (Tersariol et al. 2010) in coronal and root dentin.

The application of CHX-containing aqueous primer during the adhesive procedure did not influence the adhesion to the root canal for ER and SE adhesives (Lindblad et al. 2010; Pelegrine et al. 2010). The use of CHX to preserve the root bond strengths and the integrity of the HL with time is controversial, because some studies have shown that the application of CHX preserves the push-out bond strength in post bond cementation (Cecchin et al. 2011; Bitter et al. 2014; Toman et al. 2014), while other studies did not show any difference when compared to control after 12 months of water storage (Leitune et al. 2010; Cecchin et al. 2011; Bitter et al. 2014; Ekambaram et al. 2014). Differences in the type and brand of adhesive systems and resin cements, as well as methodological differences, can explain these controversial results.

Although lower CHX concentrations have been reported to inhibit the matrix-bound MMPs and cathepsins (Gendron et al. 1999; Scaffa et al. 2012), the application of 2 % CHX has been recommended for final root canal irrigation in endodontics because 2 % CHX solution has better antimicrobial properties than lower CHX concentrations (Mohammadi and Abbott 2009) with higher substantivity to root canal dentin (Basrani and Lemonie 2005). All these advantages may prevent long-term recontamination of the canal (Roach et al. 2001; Rosenthal et al. 2004). As no side effects in the long-term results were observed with CHX application, 2 % CHX could be considered a plausible alternative for preserving long-term bond strength.

The use of CHX-containing phosphoric acid may be an alternative to the application of an aqueous solution of 2 % CHX (Stanislawczuk et al. 2009, 2011). Although it has not been yet evaluated in root dentin, 2 % CHX results in stable bond strengths after 2 years in coronal dentin (Stanislawczuk et al. 2009, 2011) and may be considered an alternative when ER adhesives are used for adhesive procedures in the root canal.

8.3.3.2 EDTA

EDTA (ethylenediaminetetraacetic acid) is one of the most commonly used agents for irrigation during mechanical instrumentation of the root canal system. It has been also used during mechanical root periodontal therapy (Hulsmann et al. 2003). EDTA decalcifies smear-layer-covered dentin superficially, but its action is self-limiting. EDTA acts as a chelating agent, reacting with calcium ions from dentin hydroxyapatite, and forms soluble calcium salts (Hulsmann et al. 2003). As EDTA is an effective Zn^{2+} and Ca^{2+} chelator, it inhibits MMP activity (Osorio et al. 2011a; Thompson et al. 2012). In fact, EDTA has inhibitory effect against human dentin MMP-2 and MMP-9 when applied for 1–5 min (Osorio et al. 2011a; Thompson et al. 2012).

As a consequence, the use of EDTA has been suggested as a dentin pretreatment for dentin adhesives. The results showed an increase in resin–dentin bond strengths, compared to phosphoric acid and other types of dentin-conditioning agents (Torii et al. 2003; Jacques and Hebling 2005; Sauro et al. 2010). EDTA also preserved the dentin–adhesive interface in in vitro longevity tests (Sauro et al. 2010).

One drawback is that EDTA is removed from dentin by extensive rinsing with water. There may be no residual EDTA left to inhibit the activity of MMPs (Osorio et al. 2011a; Thompson et al. 2012). It has also been shown that collagen in EDTA-demineralized dentin is as susceptible to MMP degradation similarly to collagen in dentin etched with phosphoric acid (Osorio et al. 2011b). Therefore, it is not clear if the preservation of HL with EDTA is a result of a shallow dentin demineralization or from MMP inhibition.

8.3.3.3 Cross-Linkers

The base of resistance and longevity of dentin matrix is their intrinsic intermolecular and intermicrofibrillar cross-linking. So, it is believed that an increase in the extent of cross-linking of the collagen fibrils prior to adhesive application may result in increased durability (Liu et al. 2011; Bedran-Russo et al. 2014).

Collagen cross-linkers have been primarily used in demineralized dentin to enhance the mechanical properties of these substrates (Bedran-Russo et al. 2014). More recently, however, it was observed that cross-linking agents also have anti-MMP properties (Liu et al. 2011; Bedran-Russo et al. 2014), reducing the enzymatic degradation by allosteric-silencing collagenolytic enzymes or by altering the enzyme-binding site in the collagen molecule (Tjaderhane 2015). Different cross-linkers have been recently evaluated (Perdigao et al. 2013; Bedran-Russo et al. 2014). Of particular interest to dental application are the proanthocyanidins, mainly because they are a naturally occurring compound with no cytotoxicity (Bedran-Russo et al. 2014).

The major disadvantage of using cross-linking agents is that the application time needed to achieve the desirable therapeutic effect is not clinically feasible (Castellan et al. 2010, 2011). However, simplified protocols have been developed such as the incorporation of proanthocyanidins into the etchants and adhesive bottles (Green et al. 2010; Epasinghe et al. 2012; Liu et al. 2013, 2014). Unfortunately, the literature lacks sufficient evaluation of these cross-linkers for root canal use. So far, only one study evaluated the effect of proanthocyanidin application before obturation of the root canal with a resin-based sealer, reporting enhanced durability of the root canal and sealer after 3 months of water storage (Kalra et al. 2013).

8.3.3.4 Benzalkonium Chloride (BAC)

The use of aqueous solution of BAC or BAC-containing acid or adhesive may be another simpler approach to inhibit the activity of matrix-bound MMPs (Tezvergil-Mutluay et al. 2011; Sabatini and Patel 2013) as it produced more stable bonds over time for coronal dentin (Sabatini et al. 2015; Sabatini and Pashley 2015). This procedure has not yet been investigated in root dentin, but due to the similarities between coronal and root dentin, it may provide similar beneficial results.

8.4 Self-Adhesive Cements

One recent meta-analysis of laboratory studies indicated that the use of self-adhesive resin cements could improve the retention of fiberglass posts when compared with SE or ER adhesives associated to a conventional resin cement (Sarkis-Onofre et al. 2014). However, most of these studies only evaluated the immediate bonding and refer to only a specific material brand (Radovic et al. 2008; Ferracane et al. 2011). A few studies evaluated the durability of self-adhesive resin cements. Some studies reported better performance of the association of ER/SE adhesives with conventional resin cements (Mazzoni et al. 2009a; Marchesi et al. 2013), while others reported improved performance of self-adhesive cements (Leme et al. 2011; Bitter et al. 2012).

The use of MMP inhibitors did not show any improvement in longevity for self-adhesive cements (Luhrs et al. 2013), and this may be due to the superficial interaction between self-adhesive cements and dentin (Radovic et al. 2008; Ferracane et al. 2011). This means that the degradation pattern of these systems is more related to the hydrophilicity of the monomer composition. For some materials, the use of CHX can affect the immediate bonding, and clinicians should avoid the use of CHX as final irrigation when bonding with self-adhesive cements (Hiraishi et al. 2009; Luhrs et al. 2013).

8.5 Final Considerations

As final consideration, we will describe a cementation protocol used with conventional resin cements associated with SE and ER adhesives, as well as for a self-adhesive cement in order to incorporate all technical details described in this chapter.

8.5.1 Preparation of the Smear Layer

After preparation of the root canal with the appropriate bur provided by the manufacturer kit, use a diamond bur to roughen the root dentin and produce a smear layer more susceptible to dissolution (Gomes et al. 2012); rinse abundantly with water (Fig. 8.4).

8.5.2 Phosphoric Acid Etching

After trying the fiberglass post and sectioning as described in Chap. 12 (Fig. 8.5), use 34–38 % phosphoric acid, preferably in liquid viscosity, starting from the apical third of the root canal to the cervical third with agitation (Salas et al. 2011; Scotti et al. 2013) (Fig. 8.6a). It is recommended to use a BAC- or CHX-containing acid. At least one commercial brand is available on the market. Rinse with water for at least 15 s until the complete removal of all phosphoric acid (Fig. 8.6b). Use paper points to dry the root canal (Fig. 8.6c). Paper points also aid in the evaluation of

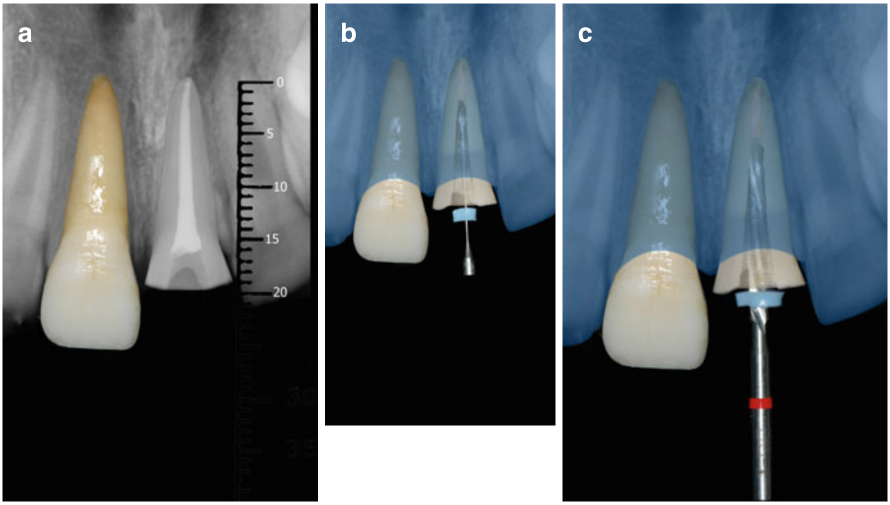

Fig. 8.4 Initial preparation. In (**a**), a radiograph evaluation of the root canal length. In (**b**), removal of the gutta-percha with a Peeso reamer. (**c**) Use a carbide bur provided by the manufacturer of the fiberglass post for preparation of the root canal. After this step, a diamond bur with similar diameter can be used to produce a smear layer more susceptible to dissolution by phosphoric acid etching. This procedure is suggested for conventional resin cements and etch-and-rinse adhesives (Clinical case gently assigned by Prof. Leonardo Muniz; Muniz 2010; reprinted with permission)

whether or not all phosphoric acid was rinsed off. This is especially important when using etchants with gel or semi-gel consistency (Fig. 8.6d). This step should be accomplished only when conventional resin cements are associated with ER adhesives.

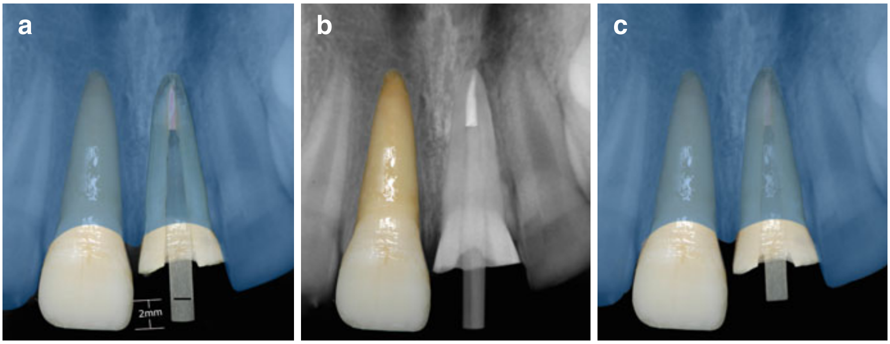

Fig. 8.5 Post preparation. (**a**) Trying in the fiberglass post into the root canal. The fiberglass post should penetrate the whole length of the preparation. This can be checked with a radiograph (**b**). The fiberglass post is sectioned as described in Chap. 12 (Clinical case gently assigned by Prof. Leonardo Muniz; Muniz 2010; reprinted with permission)

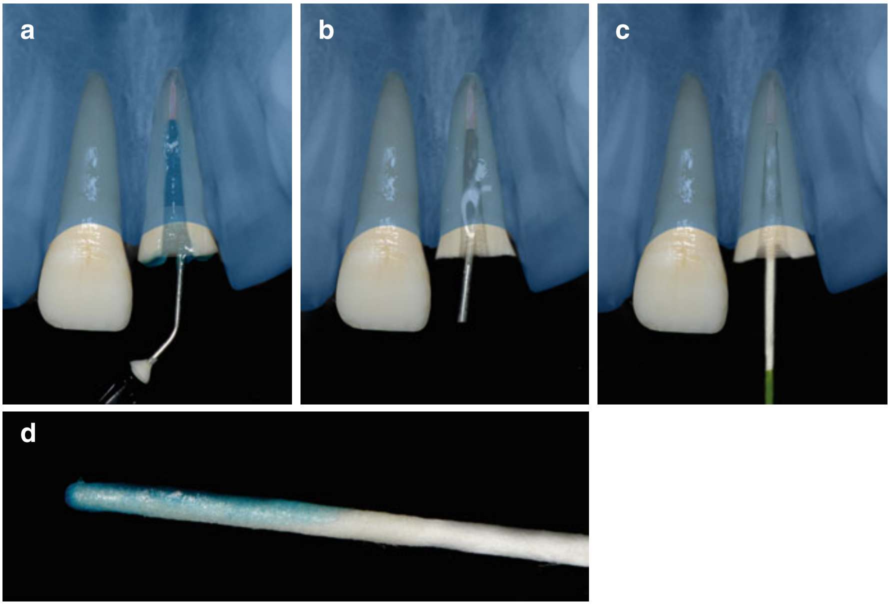

Fig. 8.6 (**a**) Etching with phosphoric acid. It is preferable to use a liquid phosphoric acid, containing chlorhexidine or benzalkonium chloride. The acid should be applied from the apical to the cervical area and then agitated. (**b**) Rinsing with water for at least 15 s or until the complete removal of all phosphoric acid (**b**). Use paper points to dry the root canal (**c**). This procedure also aids the evaluation of whether or not phosphoric acid was rinsed off (**d**). This procedure is only recommended for etch-and-rinse adhesives (Clinical case gently assigned by Prof. Leonardo Muniz; Muniz 2010; reprinted with permission)

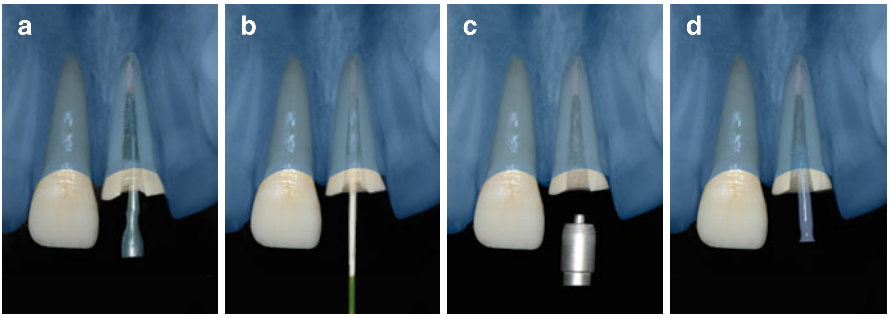

Fig. 8.7 (**a**) Application of chlorhexidine and ethanol. Apply 2 % of aqueous solution of chlorhexidine for 60 s. This step should not be performed for self-adhesive cements as it reduces the initial bond strengths. Remove excess moisture from the root canal with paper points (**b**; middle and apical third) and gentle air-drying (**c**; cervical third). In (**d**), apply a solution of 95–100 % of ethanol for 1 min, and remove excess ethanol as previously described for water (**b**, **c**) (Clinical case provided by Prof. Leonardo Muniz; Muniz 2010; reprint with permission)

8.5.3 Incorporation of Proteases Inhibitors into the Bonding Protocol

Apply 2 % CHX for 60 s (Cecchin et al. 2011; Bitter et al. 2014; Toman et al. 2014) and remove excess moisture from the root canal (Fig. 8.7). This step may be suppressed for cementation procedures performed with conventional resin cement and ER adhesives if a BAC- or CHX-containing acid was previously employed. This step should not be performed for self-adhesive cements as it reduces the initial bond strengths (Hiraishi et al. 2009; Luhrs et al. 2013).

8.5.4 Removal of Excess Water

The excess water from the cervical third and coronal part of the tooth can be removed with gentle air-drying (Fig. 8.7c). Care should be taken to avoid the dehydration of the dentin substrate prior to the adhesive application. However, this is not a simple procedure for middle and apical third. The use of paper points can allow removal of excess water from these areas (Souza et al. 2007; Thitthaweerat et al. 2013) (Fig. 8.7b).

8.5.5 Ethanol-Bonding Protocol

At this time, apply a solution of 95–100 % of ethanol for 1 min (Bitter et al. 2014; Ekambaram et al. 2014), and remove excess ethanol as previously described for water (Fig. 8.7d).

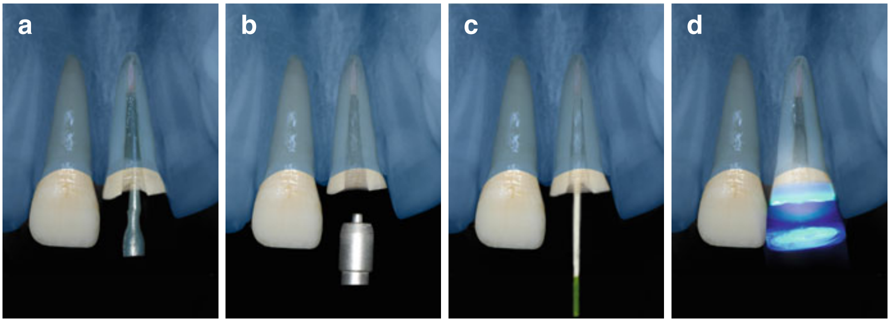

Fig. 8.8 Adhesive application. (**a**) Apply the adhesive (it is preferable to use an adhesive with an hydrophobic resin or bonding, such as a 3-step ER or a 2-step SE adhesive) inside the root canal using a rounded-tip microbrush. Apply at least two coats of adhesive to all root walls for 10–15 s actively. Remove excess pooled adhesive by gently air-drying (**b**; cervical third) and paper points (**c**; apical and middle third) between each coat. This step is suppressed when self-adhesive resin cements are used. In (**d**), the adhesive system (only light activated or dual cure) should be light-curing for prolonged exposures times 20–40 s, using a high-intensity light-curing unit (above 1000 mW/cm^2) (Clinical case gently assigned by Prof. Leonardo Muniz; Muniz 2010; reprinted with permission)

8.5.6 Adhesive Application

This step is suppressed when self-adhesive resin cements are used. Always use the full version of each adhesive strategy: three-step ER or two-step SE, in the dual-cure mode if available. If simplified adhesives are selected (two-step ER or one-step SE adhesives) the adhesive can be associated with a hydrophobic resin coating. For this purpose, the use of the adhesive bottle of any three-step ER adhesive system or two-step SE adhesive, a flowable resin or a sealant can be applied after the simplified adhesive to produce a more hydrophobic resin layer.

Apply the adhesive inside the root canal using a rounded-tip microbrush instead of a special, long brush (Souza et al. 2007) (Fig. 8.8a). Apply more than one coat of adhesive to all root walls for 10–15 s actively. Remove excess pooled adhesive with paper points (apical third) and gently air-dry (medium and apical thirds) between each coat (Souza et al. 2007; Thitthaweerat et al. 2013) (Fig. 8.8b, c).

Different approaches have been suggested to increase solvent evaporation (Souza et al. 2007; Aziz et al. 2014). Souza et al. (2007) indicated that, after application of the adhesive system, the excess of adhesive and consequently the solvent could be removed with paper points associated to air-drying (Thitthaweerat et al. 2013). More recently, Azir et al. (2014) showed that the use of an intracanal disposable plastic tip was more effective than paper points for solvent evaporation. A clear disadvantage of this last technique is that it requires special devices to be used. Regardless of the approach used, this step may be considered a very important one and should be done with much caution.

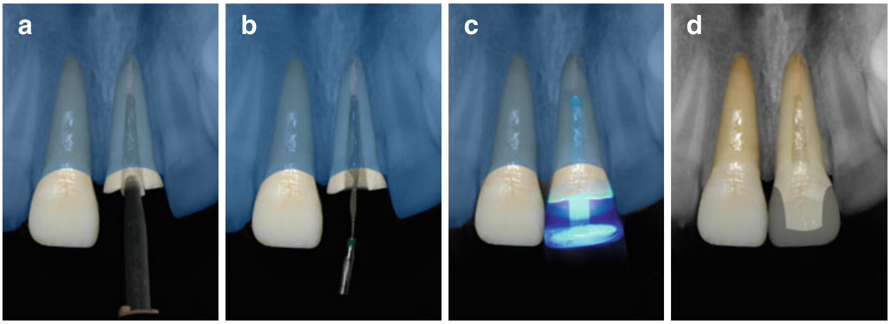

Fig. 8.9 Cementation of the fiberglass post. (**a**) Apply the resin cement inside the root canal using special long tips provided by the manufacturer of the resin cement systems (**a**) or using similar devices that allow insertion of the resin cement deep into the canal (**b**). Light-cure for at least 40 s using a high-intensity light-curing unit (above 1000 mW/cm^2) (**c**) Finally, the final restoration should be prepared and cemented according to Chap. 11 (Clinical case gently assigned by Prof. Leonardo Muniz; Muniz 2010; reprinted with permission)

8.5.7 Light-Curing Step of the Adhesive System

This step is not performed for self-adhesive resin cements. Before light curing, check if the fiberglass post seats into the desired length inside the root canal. Light-cure the adhesive system before seating the post for prolonged exposure times 20–40 s (Aksornmuang et al. 2006; Thitthaweerat et al. 2012), using a high-intensity light-curing unit (above 1000 mW/cm^2) (Fig. 8.8d). Even if using a dual-cure two-step adhesive, perform the light-curing step, because these materials do not polymerize well without light curing (Faria-e-Silva et al. 2008; Thitthaweerat et al. 2012).

8.5.8 Placement of the Resin-Luting Cement

Apply the resin cement inside the root canal using special long tips provided by the manufacturer of the resin cement or using similar devices that allow insertion of the resin cement deep into the canal (Michida et al. 2010) (Fig. 8.9a, b).

8.5.9 Light Curing the Resin Cement

Light-cure for at least 40 s using a high-intensity light-curing unit (above 1000 mW/cm^2) (Fig. 8.9c). Finally, the preparation of the final restoration and cementation procedure will be described in Chap. 12.

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Selection of Luting Materials for Bonding Fiber Posts

9

Kerstin Bitter

Abstract

Achievement of reliable bonding and effective adhesion inside the root canal is an issue of great interest. The selection of an adequate adhesive strategy inside the root canal is still a matter of debate, and data of studies demonstrate contradictory results.

After post space preparation, the dentin walls are covered by heavy smear layer containing rough debris and remnants of sealer and gutta-percha that may hamper bonding to the root canal dentin and highlight the importance of smear layer modification inside the root canal. In this aspect, the adhesive strategy might play an important role for adhesively luted fiber posts. Therefore, scientific data that have evaluated the performance of various luting materials for bonding fiber posts will be presented and analyzed.

Moreover, methods for cleaning the root canal and irrigation protocols after post space preparation and their effects on bond strength of different adhesive strategies are important clinical issues, and these aspects will also be summarized from a scientific and a practical point of view.

9.1 Introduction

Fiber posts demonstrate good biomechanical properties as a result of their elastic modulus (Young's modulus) that is considered to be comparable to that of dentin (Zicari et al. 2013). However, while the elastic modulus of hydrated dentin has been stated to be in a range between 18 and 25 GPa (Kinney et al. 2003), it seems to be

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dependent upon the region inside the dentin and the amount and direction of the dentinal tubules resulting in a transition from structural isotropy to anisotropy (Bar-On and Daniel Wagner 2012). Consequently, adhesively luted fiber posts may not resemble a complex structure like dentin. Nevertheless, the mechanical properties of fiber posts are closer to those of dentin compared to stiffer materials, such as metal posts. Therefore, the risk of catastrophic failures when using fiber posts might be reduced (Fernandes et al. 2003). In spite of these assumptions, a recent prospective clinical study did not reveal a significant difference in survival rates between metal and fiber posts after an observation period of 7 years (Sterzenbach et al. 2012a).

Failure of fiber posts occurs more often through decementation or post fracture than because of root fracture (Naumann et al. 2012). Consequently, the adhesive luting procedure of fiber posts is an important factor for the restoration of endodontically treated teeth. Adhesive luting is complicated due to the high C-factor inside the root canal (Tay et al. 2005). Moreover, limited visibility and control of moisture content of the root canal dentin as well as irregular structures of secondary dentin and cement and a reduced amount of dentinal tubules in the apical part of the root canal may hamper the adhesive luting procedure inside the canal (Mjör et al. 2001). In addition, other factors might affect the retention of fiber posts inside the root canal, such as the cleanliness of the post space, the selection of the sealer for root canal filling, the final irrigation protocol prior to post insertion, as well as the post fit inside the root canal. These aspects are described in detail in this chapter.

9.2 Factors That Could Affect Fiber Post Bond Strength and Stability

9.2.1 Cleanliness of the Post Space Preparation

Various studies demonstrated remnants of sealer and gutta-percha inside the root canal after post space preparation that may interfere with adhesive luting of fiber posts inside the root canal (Serafino et al. 2004; Perdigao et al. 2007a). Figure 9.1 shows examples of the cleanliness of the post space preparation under a stereomicroscope. The four images demonstrate a clean post space (Fig. 9.1a), remnants of sealer (Fig. 9.1b, c), and remnants of sealer and gutta-percha inside the root canal (Fig. 9.1d).

Mechanical cleaning methods, such as sandblasting using aluminum oxide particles or rotary instrumentation using brushes and pumice, have been analyzed with regard to their cleaning effectiveness inside the post space preparation as well as their effects on the retention of fiber posts (Bitter et al. 2012). The cited in vitro study did not detect any positive effects of the mentioned cleaning methods on the root canal cleanliness, indicating that the limited accessibility of the root canal for the intraoral sandblasting device may hamper its effectiveness inside the root canal. However, SEM observations of the investigated specimens detected effects of sandblasting on the root canal dentin (Fig. 9.2b). Moreover, SEM micrographs revealed layers of sealer inside the root canal that were located on top of the smear layer

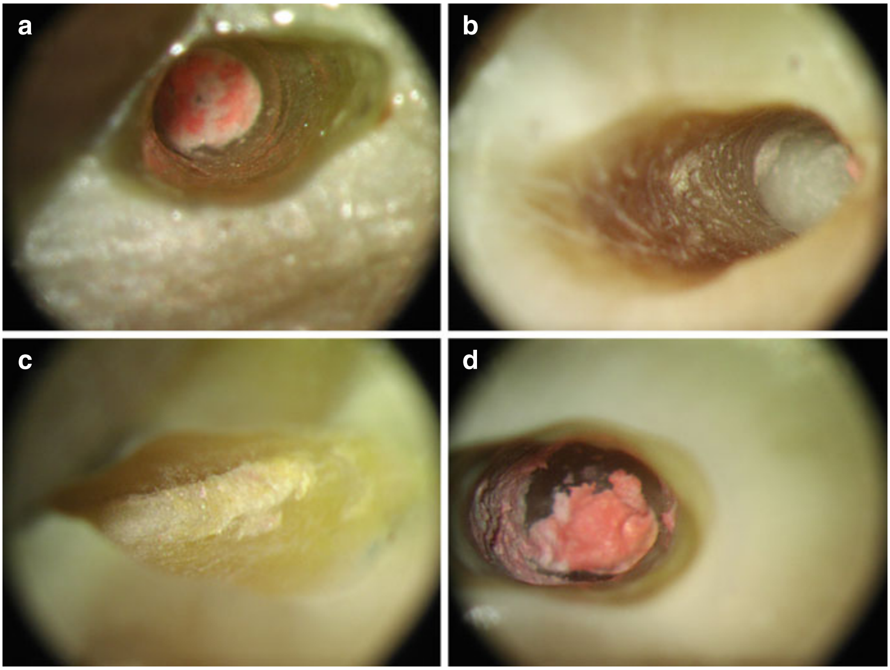

Fig. 9.1 (**a**) Clean post space after post space preparation and irrigation of the root canal. (**b**): Small remnants (**c**) large remnants of sealer, whereas (**d**) reveals large remnants of sealer and gutta-percha

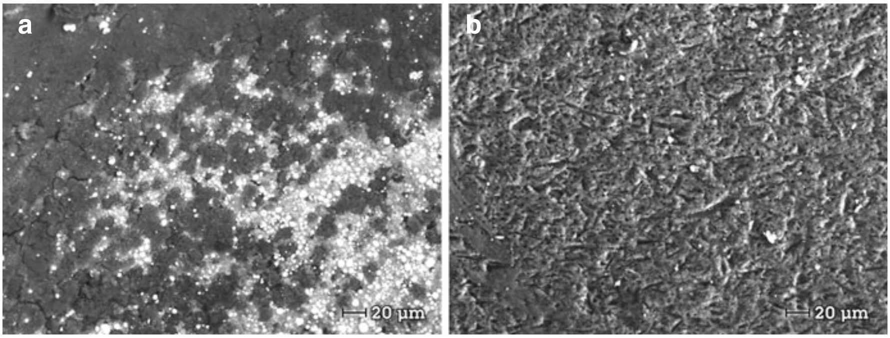

Fig. 9.2 (**a**) SEM micrograph of root canal dentin demonstrating layers of sealer that are located on top of the smear layer that covers the dentinal tubules. (**b**) SEM micrograph depicting marginal grooves resulting from sandblasting

(Fig. 9.2a) indicating that cleaning of the root canal prior the application of adhesive techniques is of great importance for gaining optimal adhesion inside the root canal.

In the study cited above (Bitter et al. 2012), the retention of fiber posts was significantly reduced when the root canal was cleaned using rotating brushes and pumice; therefore, this cleaning method is not recommended without further final irrigation protocols (Bitter et al. 2012). Another investigation demonstrated that sonically activated canal brushes were effective in removing the smear layer inside the root canal when used in combination with 17 % EDTA (Salman et al. 2010). These results are supported by another in vitro study that revealed that the combination of ultrasonic irrigation and 17 % EDTA resulted in satisfactory canal debridement and tubule opening (Coniglio et al. 2008).

After root canal filling and post space preparation, the root canal walls are usually coated with remnants of sealer and gutta-percha, as well as smear layer and dentin debris. Consequently, cleaning of the post space using higher magnification for visualizing the post space is indispensable. Mechanical cleaning using hand instruments or files should be combined with a final irrigation protocol that will be explained in detail in this chapter later on.

9.2.2 Selection of Sealers for Root Canal Filling

Figure 9.1 revealed that remnants of sealer might hamper adhesion inside the post space preparation. Various studies analyzed in vitro the effect of different endodontic sealers on the retention of fiber posts (Demiryurek et al. 2010; Aleisa et al. 2012; Vano et al. 2012; AlEisa et al. 2013; Mesquita et al. 2013). In studies of one working group, eugenol-based sealers reduced the retention of fiber posts luted with resin cements compared to epoxy resin-based sealers (Aleisa et al. 2012; AlEisa et al. 2013). These effects may be attributed to remnants of phenolic components that can collect free radicals and delay the polymerization reaction when interacting with resin (Mayer et al. 1997). However, other researchers concluded that the chemical formulation of endodontic sealers did not affect the retention of posts luted with resin cements (Hagge et al. 2002; Kurtz et al. 2003) or the marginal seal of adhesively luted carbon fiber posts (Mannocci et al. 2001). Nevertheless, unobturated controls revealed significantly higher retentive post strengths compared to root-filled groups indicating that remnants of sealer might hamper adhesion inside the root canal (Boone et al. 2001; Hagge et al. 2002).

Another fact is the length of time that eugenol-containing materials remain in contact with dentin until removal; a longer contact time might reduce adhesion (Hagge et al. 2002). Therefore, it has been suggested that effective removal of eugenol-based sealers should be performed immediately after obturation. On the other hand, delayed post space preparation 24 h or 7 days after obturation using a eugenol-based sealer followed by adhesive luting of fiber posts demonstrated significantly higher bond strength compared to immediate post space preparation and adhesive post luting (Vano et al. 2012). Equal results were obtained for an epoxy resin-based sealer (Vano et al. 2008). The authors speculated that contamination of the post space might be minimized when the sealer is allowed to set completely prior post space preparation. In all referenced papers, no final irrigation protocol except rinsing using tap water after post space preparation was applied; consequently the effects of the sealer type on the adhesion properties inside the root canal might be reduced when using a final irrigation protocol that has positive effects on the cleanliness of the post space cavity.

In conclusion, the effects of different types of sealer on adhesion of resin cements inside the root canal and the retentive strength of posts remain controversial, although the literature revealed a tendency towards a negative effect of eugenol-based sealers. It has been reported that this problem might be avoided by thorough cleaning of the root canal walls (Schwartz and Robbins 2004); moreover, the adhesive procedure inside the root canal will benefit the most from a perfect clean root dentin surface that is not contaminated with any kind of sealer.

9.2.3 Final Irrigation After Post Space Preparation

The smear layer is formed during post space preparation and consists of remnants of root canal dentin, gutta-percha, and sealer. Moreover, the smear layer may be plasticized because of the frictional heat of the drill (Khalighinejad et al. 2014). Besides mechanical cleaning methods that have been mentioned above, various chemical agents such as sodium hypochlorite (NaOCl), ethylenediaminetetraacetic acid (EDTA), chlorhexidine (CHX), ethanol, or combinations of these agents have been used to test their ability to remove the smear layer inside the root canal and their effects on bond strengths of fiber posts (Carvalho et al. 2009; Lindblad et al. 2010, 2012; Cecchin et al. 2011; Bitter et al. 2013; Bitter et al. 2014a; Khalighinejad et al. 2014). In this regard, it should be considered that NaOCl and EDTA are common endodontic irrigants, although their prolonged use at high concentrations may have negative effects on the physical properties of root canal dentin, such as reduced flexural strength, elastic modulus, and microhardness (Tang et al. 2010). These changes of the structural properties of dentin may affect the bond strengths between adhesives and luting agents to root canal dentin (Dogan Buzoglu et al. 2007). Consequently, irrigation after post space preparation and its effects on the bond strength of different adhesive strategies are a matter of interest, in particular because manufacturers' recommendations vary from the use of sodium hypochlorite (NaOCl) to no recommendations at all. With this in mind, five different irrigation protocols after post space preparation were investigated in vitro to analyze their effects on bond strengths of fiber posts to root dentin using three different adhesive strategies (Bitter et al. 2013). Besides a control group using distilled water, the irrigation protocols were passive ultrasonic irrigation (PUI) using NaOCl 1 and 5.25 %, respectively. Additionally, irrigation using 18 % EDTA followed by 5.25 % NaOCl as well as 2 % CHX was tested after post space preparation. Fiber posts were luted using a self-etch and an etch-and-rinse adhesive system as well as a self-adhesive resin cement. The effects of the irrigation protocol on bond strengths were significantly affected by the adhesive strategy. For the etch-and-rinse adhesive system, irrigation using EDTA and NaOCl 5.25 % resulted in significantly lower mean bond strengths compared to the control group, whereas irrigation using NaOCl 1 % with PUI revealed the highest mean bond strengths. These results were supported by the analyses of the adhesive interface using confocal laser scanning microscopy

(CLSM) in dual-fluorescence mode (Fig. 9.3 a–c), which demonstrated a deep infiltration of adhesive and luting cement into the strongly demineralized root canal dentin. Although the demineralizing effect of 18 % EDTA and 5.25 % NaOCl would be desirable in terms of smear layer removal, alteration of the chemical structure of the underlying dentin, especially in combination with phosphoric acid, might result in extensive demineralization with suboptimal adhesion. Consequently, this irrigation protocol cannot be recommended for etch-and-rinse adhesive systems.

The mean bond strengths of the self-etch adhesive system used in this study were not affected by the different irrigation protocols. These results were confirmed by other in vitro studies (Zhang et al. 2008; Fawzi et al. 2010). Effective removal of the smear layer and deeper penetration of adhesive system and resin cement were also visualized using CLSM (Fig. 9.4a–c); however, this did not correlate with an increase in bond strength.

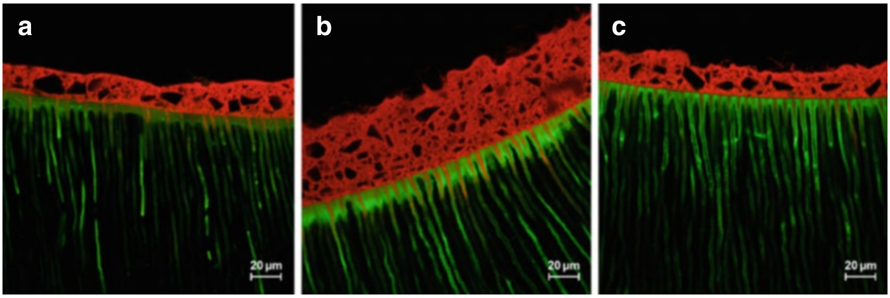

Fig. 9.3 (**a**–**c**) Representative microscopic images using CLSM for the etch-and-rinse adhesive XPBond/Self Cure Activator with Core X Flow (DENTSPLY DeTrey) after irrigation of the post space preparation using NaCl (**a**), 18 % EDTA/5.25 % NaOCl (**b**), and 1 % NaOCl (**c**). (**b**) shows increased penetration of *red*-labeled core material into dentinal tubules and funnel-shaped resin tags filled with *green*-labeled adhesive. (**c**) shows a homogenous hybrid layer and continuous penetration of core material into dentinal tubules compared to the control group (**a**)

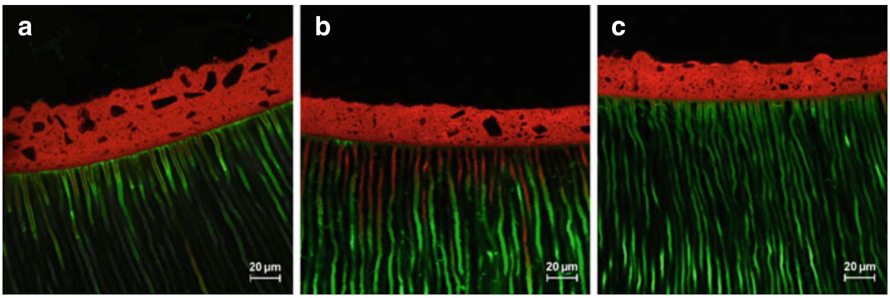

Fig. 9.4 (**a**–**c**) Images of the self-etch adhesive system AdheSE DC (*green*) used with Multicore Flow (*red*) Ivoclar Vivadent. Irrigation of the post space preparation using 18 % EDTA/5.25 % NaOCl (**b**) leads to increased penetration of core material into the dentinal tubules indicating effective smear layer removal of this irrigation protocol. Irrigation of the post space using 1 % NaOCl (**c**) revealed a tendency of more penetrated tubules with core material compared to the control group (**a**); a thin but continuous hybrid layer formation was observed in all groups

For the self-adhesive resin cement, smear layer removal with 18 % EDTA and 5.25 % NaOCl resulted in significantly higher-mean bond strengths compared to the control group (Bitter et al. 2013). These effects were visualized using CLSM (Fig. 9.5a–c). A deeper penetration of the resin cement into the dentinal tubules was evident. Consequently, each adhesive strategy need to be adapted to a specific irrigation protocol; however, irrigation using 1 % NaOCl applied with passive ultrasonic activation resulted in high-mean bond strength for all groups. Consequently, this protocol can be recommended for smear layer removal after post space preparation irrespective of the adhesive strategy.

Besides initial bond strength testing, durability of adhesion inside the root canal is an important factor for the longevity of postendodontic restoration using fiber posts and explained in detail in Chap. 8. One strategy to prevent degradation of resin dentin bonds is the application of matrix metalloproteinase (MMP) inhibitors to the demineralized collagen matrix prior to the application of dentin adhesives. For more details, the reader is referred to Chap. 8. For final irrigation, CHX has been used as a nonspecific MMP inhibitor during adhesive application, and inside the root canal, it did not negatively affect immediate and long-term bond strength in post bond cementation (Lindblad et al. 2010, 2012; Cecchin et al. 2011). However, other studies revealed a significant decrease of fiber post bond strength to CHX-treated root canal dentin after thermocycling and storage (Bitter et al. 2014a) or thermomechanical loading (Cecchin et al. 2014).

A simplified procedure of the ethanol wet bonding technique, which is explained in detail in Chap. 8, is to irrigate the root canal using 99 % ethanol prior to application of the adhesive system or the luting agent. This procedure was able to prevent a decrease in bond strength after thermomechanical loading (Cecchin et al. 2014) as well as after thermocycling and storage for an etch-and-rinse adhesive as well as for a self-adhesive resin cement in the middle and apical part of the root canal (Bitter et al. 2014a). This leads to the assumption that insufficient moisture control in the depths of the root canal might be compensated with the application of ethanol probably rendering the collagen matrix more hydrophobic by replacing water with

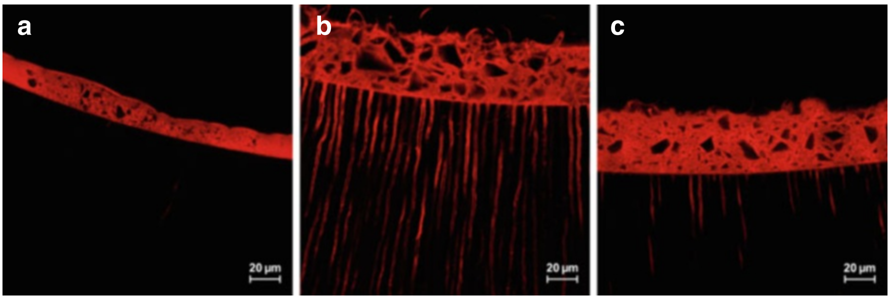

Fig. 9.5 (**a**–**c**) CLSM images of the self-adhesive resin cement SmartCem2 (DENTSPLY DeTrey). Irrigation of the post space using 18 % EDTA/5.25 % NaOCl revealed an increased number of resin-filled dentinal tubules (**b**), whereas the number of resin-filled tubules was reduced for irrigation using 1 % NaOCl (**c**). No resin tags were observed in the control group (**a**)

ethanol. However, the effects of ethanol pretreatment of the root canal dentin on fiber post bond strength seem to depend on the composition of the adhesive system used (Carvalho et al. 2009; Cecchin et al. 2011). Therefore, more research on this field is required until final recommendation can be given despite the present results on the effects of ethanol pretreatment of the root canal dentin seem to be promising.

9.2.4 Pretreatment of Fiber Posts

SEM observations in Fig. 9.6 illustrate examples for possible failure modes of adhesively luted fiber posts, i.e., adhesive failure between root canal dentin and cement (a) and adhesive failure between post and cement (b).

Consequently, a reliable bond to the post surface, as well as to the root canal dentin, is mandatory for establishing durable post-endodontic restorations. Although failures at the interface between root canal dentin and luting agent seem to occur more often (Rasimick et al. 2010), numerous pretreatment procedures of fiber posts have been suggested to enhance the bond strength between fiber post surface and luting agent.

Current fiber posts consist of unidirectional fibers (glass or quartz) that are embedded in a resin matrix. Different matrices are used by the manufacturers, i.e., epoxy resin, methacrylate resin, or a proprietary resin (Zicari et al. 2012a). It has been demonstrated that different glass fiber posts may vary in flexural properties and micromorphology and that flexural properties may be affected by mechanical properties of the resin matrix and interfacial adhesion between fiber and matrix (Zicari et al. 2013). Moreover, differences in micromorphology, surface texture, and composition may have an impact on the effects of post-pretreatment on fiber post bond strength. Chemical and micro-mechanical pretreatment protocols of fiber posts have been analyzed with the aim to increase bond strength between post

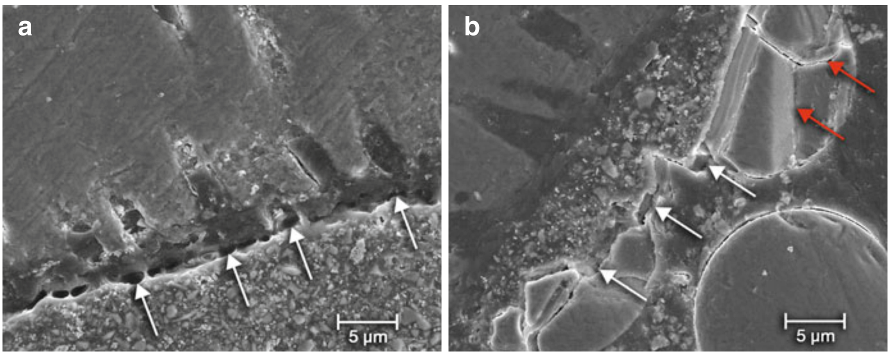

Fig. 9.6 (**a**) SEM image of an adhesive failure (*arrows*) between root canal dentin and luting cement. (**b**) SEM image of an adhesive failure between fiber post and luting cement (*white arrows*); damage of the fiber is visible (*red arrows*)

surface and resin luting agent. The most common micro-mechanical post-surface pretreatment methods include sandblasting and application of the Cojet System (3M ESPE). The goal of sandblasting is to remove the top layer of resin in order to expose glass fibers for possible chemical interaction as well as roughening the surface. Data in the literature indicate that sandblasting enhanced bond strength of fiber posts (Balbosh and Kern 2006); however, the effects of sandblasting on bond strength of fiber posts with and without additional silane application seem to depend on the post type and the luting cement (Magni et al. 2007; Radovic et al. 2007). Moreover, sandblasting resulted in undesirable alterations of the post surface with a disruption of the interface between matrix and fiber that lead to fractures of superficial fibers after mechanical loading (Soares et al. 2008). Consequently, a weakening effect of sandblasting on long-term fiber post stability cannot be excluded. The Cojet System uses silica-coated alumina particles resulting in a tribochemical coating of the post surface, which can then be silane-treated (Zicari et al. 2012a). Again, controversial data exists on the effects of fiber post-pretreatment using the Cojet System (Bitter et al. 2006; Zicari et al. 2012a), and the effects were also significantly affected by fiber post type and luting cement. Fiber damage has also been observed (Fig. 9.7a, b).

Clinically, silanization of the post surface is the most often employed chemical pretreatment procedure. However, this pretreatment procedure has resulted in contradictory results (Goracci et al. 2005; Perdigao et al. 2006; Bitter et al. 2007; Zicari et al. 2012a). The main effects of silane pretreatment are based on improved wettability of the surface as well as chemical bridge formation between filler particles and fibers of the post and the resin matrix of adhesive or resin cement (Zicari et al. 2012a).

The effects of this pretreatment seem to be strongly dependent on the composition and micromorphology of the post surface (i.e., reachable fibers and filler particles at the surface of the post) and the composition of the applied adhesive or resin cement. Moreover, it has been speculated that the interface produced between resin cements and silanized posts might be affected by the phenomenon of hydrolytic

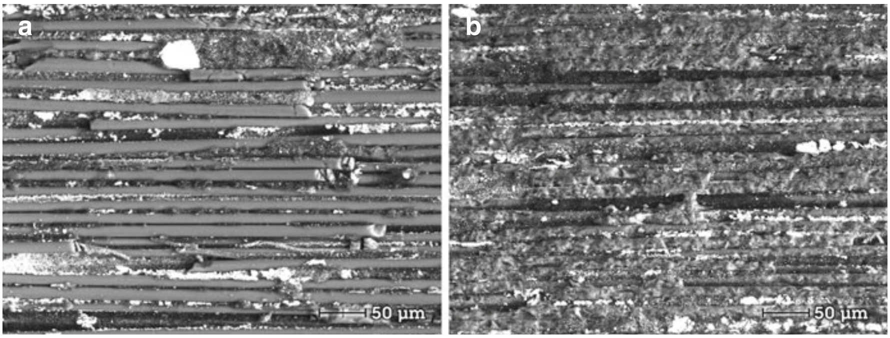

Fig. 9.7 (**a**, **b**) Post surface of a fiber post (FRC Postec, Ivoclar Vivadent) with a dimethacrylate-based matrix: (**a**) untreated and (**b**) after exposure to Cojet (3M ESPE). Damage of the surface of the fibers is visible

weakening hampering the proper interaction between these materials (Machado et al. 2015). The application of a hydrophobic resin adhesive on a previously silanized post increased fiber post retention in vitro probably due to a reduction of hydrolysis (Machado et al. 2015).

Further combined chemical and micro-mechanical pretreatment procedures include the application of hydrofluoric acid followed by silanization (Monticelli et al. 2008a; Schmage et al. 2009a) that resulted in an increased fiber post bond strength dependent on the luting agent used. However, the effect of the acid on the post surface has been proven to be time dependent and affected by the post composition (type of matrix and/or fibers). With regard to the application time of the acid, this technique produced substantial damage to the glass fibers and affected the integrity of the post (Valandro et al. 2006).

Other pretreatment procedures of fiber posts, such as immersion into hydrogen peroxide (Vano et al. 2006) or the use of sodium ethoxide (Monticelli et al. 2006a), aimed to dissolve the epoxy or methacrylate-based resin matrix of the post surface and concomitant exposure of undamaged fibers, thus leading to increased bond strengths to resin luting agents after application of silane. Etching of the post surface for 20 min using 10 % hydrogen peroxide increased bond strength between resin luting agent and fiber post (Monticelli et al. 2006b); however, this procedure seems to be not suitable for daily clinical practice.

Recently, surface polydopamine functionalization was found to be effective in improving the bond strength between resin luting agents and fiber posts without damaging the fiber post surface (Chen et al. 2014). More research is needed to evaluate whether this surface modification also leads to long-term bond stability.

To simplify the clinical procedure, posts with a pre-coated surface have been introduced onto the market (Fig. 9.8). Posts are either etched using hydrofluoric acid, vapor coated using silicon oxide, and silanized by immersion followed by a coating with MMA that should penetrate into the post surface (DT Light Post SL, VDW) or tribochemical coated, silanized, and protected with a 25-µm-thick polymer coating (ER Dentin Post Coated, Gebr. Brassler). Few studies analyzed the

Fig. 9.8 Clinical example of try-in of a pre-coated fiber post – Dentin Post Coated (Komet)

effect of pre-coating on fiber post bond strength compared to untreated posts and found limited effects that were also affected by the luting agent used. For the self-adhesive resin cement RelyX Unicem, no increase in bond strength was observed for either pre-coated post (Mazzitelli et al. 2012a; Schmage et al. 2012).

Although numerous pretreatment procedures of fiber posts have been intensively studied, more failures at the interface between dentin and resin luting agent have been observed clinically (Rasimick et al. 2010). Nonetheless, optimal adhesion should be achieved at the fiber post-resin luting interface. Unfortunately, no general recommendations can be given because the effects of the various pretreatment procedures were strongly dependent on the micromorphology of the post surface and the composition of the matrix as well as on the resin luting agent used. Aggressive pretreatment procedures such as sandblasting, Cojet treatment, or application of hydrofluoric acid may damage fibers and possibly affect post integrity and should therefore be avoided. Improved wetting of the post surface, as well as compatibility between resin luting agent and matrix of the post, seem to be important factors for optimal fiber post bond strength.

9.2.5 Post Fit and Resin Cement Layer Thickness

Maximum adaptation of the post to canal walls is essential to improve retention and fracture resistance when nonadhesive post cementation is performed using zinc phosphate cement (Sorensen and Engelman 1990). For adhesively luted fiber posts, it has been suggested that perfectly fitting posts are not necessarily required (Perdigao et al. 2007a; Krastl et al. 2011); moreover, in noncircular root canals, a uniform cement layer thickness is often not achievable besides invasive post space preparation would be performed. This should be avoided, because substance loss and modification of the natural root canal geometry play important roles in tooth rigidity (Lang et al. 2006). The presence of inner dentine located adjacent to the root canal has a major impact on tooth fracture resistance, and consequently, structurally sound inner dentine should be preserved whenever possible (Kishen et al. 2004).

However, the resistance to occlusal loading is higher if a post with a greater diameter is used. Thinner posts are more susceptible to fracture than thicker posts, especially when there is a difference between root canal and post diameter (Lazari et al. 2013). On the other hand, the C-factor is strongly elevated when a post is inserted, and this was associated with a significant decrease in bond strength (Aksornmuang et al. 2011). Although a larger resin cement layer thickness resulted in a lower C-factor compared to a thin cement layer thickness, the contraction stress within a thin resin composite layer had only a minuscule change with each 100 μm difference in layer thickness (Alster et al. 1992). Consequently, small changes in resin cement layer thickness did not automatically affect fiber post push-out bond strength (Perez et al. 2006; Perdigao et al. 2007a; Aksornmuang et al. 2011) or fracture resistance (Buettel et al. 2009), indicating that a perfect fit of adhesively luted fiber posts is not necessarily required. A recent finite-element analysis revealed that the thinner the cement layer, the higher the stress concentration on it (Lazari et al. 2013). Conversely, another study found that thickness of the resin cement layer did not affect stress concentration at the cement interface (Spazzin et al. 2009). It has been concluded that the elastic modulus of the resin cement is more important to the stress concentration than the thickness of this layer. Other researchers found that oversized post space preparation resulted in lower push-out (Egilmez et al. 2013) or pull-out force (D'Arcangelo et al. 2007; Schmage et al. 2009b). Nevertheless, the effects on bond strength were affected by the type of the resin luting agent used and the definition of oversize post space.

In conclusion, invasive post space preparations should be avoided because of substance loss and modification of the natural root canal geometry that might affect the fracture resistance of root canal-treated teeth. Additionally, the indication of additional post space preparation for fiber post insertion should be reconsidered critically in daily practice and limited to situations were firstly a post is required for retention of the coronal restoration and secondly the width of the root canal needs further enlargement for post insertion. Perfectly fitting posts that result in small resin cement layer thickness are not necessarily required; therefore, additional conventional post space preparation is not mandatory in every clinical case and alternative post space preparations, for example, using ultrasonic tips (Rengo et al. 2014) or round burs (Bitter et al. 2012) should also be taken into consideration as well as the selection of a post that already fits into the existing root canal.

9.3 Luting Agents and Systems for Fiber Post Bonding

9.3.1 Selection of Adhesive Systems for the Root Canal: Etch-and-Rinse vs. Self-Etch

Besides the factors that may affect bond strength of fiber posts inside the root canal, additional aspects should also be taken into consideration, including the hydration degree of dentin, the difficult moisture control inside the root canal, as well as the lack of view into the root canal that can affect the bonding process (Zicari et al. 2008). The bonding protocols of restorations adhesively luted to coronal dentin are similar to those recommended for bonding fiber posts into the root canal. However, bond strengths to root canal dentin are generally lower compared to those to coronal dentin. Multi-step composite-based cements are available to be used as "etch-and-rinse" or "self-etch" strategies (Zicari et al. 2012b). The smear layer created in the root canal walls as a result of motorized preparation, such as with post drills, is thicker compared to the smear layer created with manual instrumentation of the root canal (Czonstkowsky et al. 1990). Based on morphological analyses of the adhesive interface inside the root canal, it has been speculated that the use of phosphoric acid inside the canal might be advantageous with respect to dissolving the thick and dense smear layer (Bitter et al. 2004). However, the "self-etch" strategy has been claimed to be more user-friendly and less-technique-sensitive compared to the "etch-and-rinse" approach (Van Meerbeek et al. 2011). These aspects might be even more relevant because of the unfavorable conditions inside the root canal, especially with respect to moisture control. Morphological analyses of the adhesive interface of both adhesive strategies inside the root canal using dual-polymerizing bonding agents have been performed using CLSM (Bitter et al. 2014b). As expected, the analysis of the adhesive interface demonstrated thicker hybrid layers for "etch-and-rinse" adhesive systems compared to "self-etch" adhesive systems (Bitter et al. 2014b) (Fig. 9.9a, b). However, a continuous thin hybrid layer and a tight interface had been observed for the self-etch adhesive systems in the referenced study, indicating successful smear layer modification for the adhesive systems used. These adhesive systems contain co-initiators, such as benzene sulfinic acid sodium salt (Arrais et al. 2007). The initiator-catalyst system should promote adhesion of compatible dual-cured resin-based luting agents to the adhesive layer and accelerate their polymerization (Arrais et al. 2009). Therefore, differences in light transmission of different kinds of fiber posts (Goracci et al. 2008) should not hamper the bonding performance of different adhesive systems.

Regarding the bonding effectiveness of these two adhesive strategies inside the root canal, conflicting results have been reported. Two studies revealed no significant difference between the two adhesive strategies (Mazzoni et al. 2009; Bitter et al. 2014b), whereas others reported lower bond strength for "etch-and-rinse" adhesives compared to "self-etch" adhesives (Zicari et al. 2008; Bitter et al. 2009a). In contrast, another study showed lower bond strengths for the "self-etch" approach compared to the "etch-and-rinse" or "self-adhesive" approach (Radovic et al. 2008). These conflicting results imply that bond strength inside the root canal seems to be more material dependent than adhesive strategy dependent. A recently review on bond strength performance of resin luting cements inside the root canal demonstrated no difference in mean bond strengths between "self-etch" and

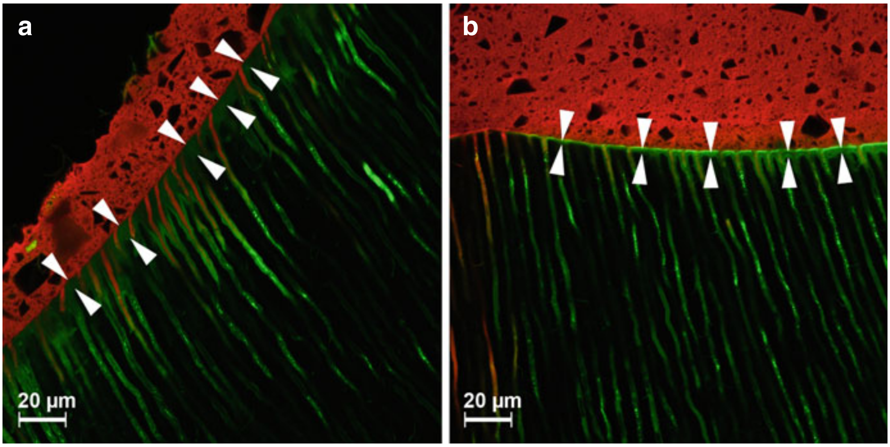

Fig. 9.9 (**a**, **b**) Microscopic images using CLSM for the measurement of the hybrid layer (DENTSPLY DeTrey) (*indicated with arrows*) for the etch-and-rinse adhesive XP Bond/Self Cure Activator with Core X Flow (**a**) and for the self-etch adhesive system Futurabond DC with Rebilda DC (VOCO GmbH) (**b**)

"etch-and-rinse" adhesives in combination with a conventional resin cement (Sarkis-Onofre et al. 2013). This same study also reported a high heterogeneity among studies.

Bonding performance and sealing ability of luting agents inside the root canal may be further affected by the intensity of chemical interaction between adhesive and dentin (Van Meerbeek et al. 2011), the presence of a non-encapsulated zone beneath the hybrid layer that could affect the long-term bonding performance (Pashley et al. 2011) as well as polymerization shrinkage stress and the degree of polymerization of the resin cement (Zicari et al. 2008). These factors are highly dependent on the product used, indicating again that this factor seems to be more important than the adhesive approach.

9.3.2 Performance of Self-Adhesive Resin Cements for Bonding Fiber Posts

Self-adhesive resin cements are designed to adhere to the tooth substrate without separate application of adhesive or etchant. They can be classified as two-part materials that are composed of methacrylate monomers and acid-functionalized methacrylate monomers. The latter functionalized monomers include predominantly either carboxylic or phosphoric acid groups that perform demineralization of the tooth substrate and promote stable salt formation, mainly involving calcium (Ferracane et al. 2011). *More details are mentioned in* Chap. 8. This simplified and less-technique-sensitive adhesive approach seems to be a satisfactory luting procedure for the root canal, where the steps involving application of adhesive systems are difficult to control (Zicari et al. 2012b). The first commercially available self-adhesive resin cement was RelyX Unicem (3M ESPE). Consequently, the vast majority of the literature has included this self-adhesive resin cement for bonding fiber posts (Sarkis-Onofre et al. 2013). The manufacturer claims a high tolerance to moisture because water is formed during the neutralization reaction of phosphoric acid methacrylate, basic fillers, and hydroxyapatite (Zicari et al. 2012b). Limited interaction in terms of smear layer removal and tag formation have been demonstrated (Al-Assaf et al. 2007) and visualized (Figs. 9.10 and 9.11) (Bitter et al. 2009b).

However, a good chemical interaction with calcium of hydroxyl apatite has been described for self-adhesive resin cements (Monticelli et al. 2008b). This is corroborated by a recent review that revealed that the use of self-adhesive resin cement might improve bond strength of fiber posts inside the root canal (Sarkis-Onofre et al. 2013) indicating that this simple and less-technique-sensitive procedure is advantageous. The same cement demonstrated less nanoleakage compared to multi-step resin cements inside the root canal when fiber posts were luted (Bitter et al. 2011). In addition, good clinical performance has been shown for adhesively luted fiber and titanium posts using the self-adhesive resin cement RelyX Unicem (Sterzenbach et al. 2012a). It has been speculated that the higher bond strength of self-adhesive resin cements inside the root canal may be related to the lower polymerization stress compared with multi-step resin cements (Frassetto et al. 2012; Sarkis-Onofre et al. 2013), although mechanical properties and bonding

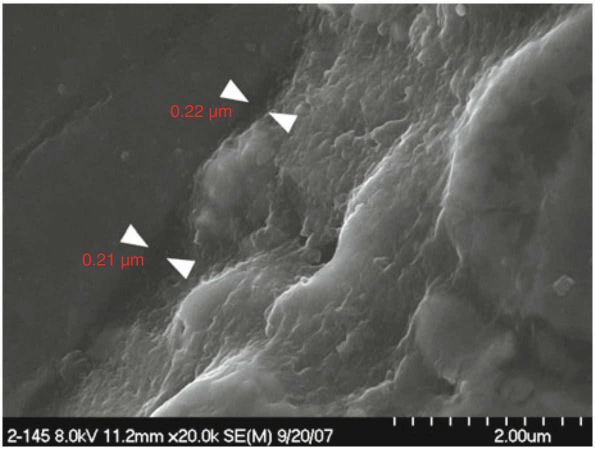

Fig. 9.10 SEM image of the interface between RelyX Unicem and root canal dentin (3M ESPE). *Arrows* indicate a very thin hybrid layer of 0.2 µm

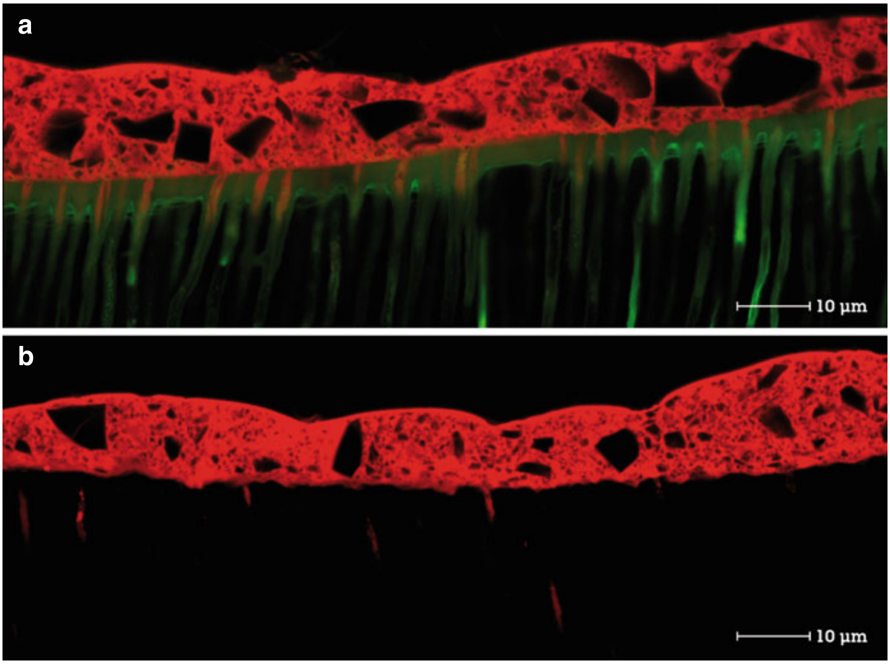

Fig. 9.11 CLSM image demonstrated for the resin core material CoreX Flow and the etch-and-rinse and adhesive XP Bond applied with Self Cure Activator (DENTSPLY DeTrey) a distinct hybrid layer and numerous resin tags filled with adhesive and resin core materials (**a**). For the self-adhesive resin cement SmartCem2 (DENTSPLY DeTrey) no hybrid layer formation was detected and penetration into the dentinal tubules occurred only sporadically (**b**)

performance of self-adhesive resin cements are very product dependent (Frassetto et al. 2012; Mazzitelli et al. 2012b). Another fact for good bonding performance of the self-adhesive resin cement RelyX Unicem inside the root canal might be the pressure exerted during post insertion, because it has been previously highlighted that RelyX Unicem must be always applied under pressure to ensure that the cement intimately adapts to the cavity walls in order to obtain high bond strength (De Munck et al. 2004). Therefore, it can be concluded that luting fiber posts using a self-adhesive resin cement appears to be a reliable and suitable, as well as less-technique-sensitive, option inside the root canal. Recently, a study pointed out negative effects in terms of damage of glass ceramic crowns when using a self-adhesive resin cement as core buildup material (Sterzenbach et al. 2014). Damage of glass ceramic crowns occurred after long-term water storage and the authors speculated that hygroscopic expansion of the self-adhesive resin cement used in the study might be responsible for the observed cracks. Consequently, the use of these materials as core buildup material cannot be recommended.

9.3.3 Post-and-Core Systems

An advantage for the clinical application of fiber posts is the combination of luting the post inside the root canal and performing the core buildup in a one-stage procedure. This is a time-saving and user-friendly approach. Consequently, various manufacturers provide post-and-core systems and recommend the procedure (Bitter et al. 2014b). This combination has been described as a secondary monoblock (Tay and Pashley 2007). However, a previous study pointed out possible negative effects of core materials for luting fiber posts due to the higher filler content (Ferrari et al. 2009).

Post-and-core-systems are available with the different adhesive approaches described in this chapter, i.e., "self-etch" or "etch-and-rinse" adhesive systems. Data of testing core materials for luting fiber posts in vitro varied greatly among products and adhesive systems used (Mazzoni et al. 2009; Schmage et al. 2009a; Schmage et al. 2009b; Rodig et al. 2010; Schmage et al. 2012; Bitter et al. 2014b). When testing solely post-and-core materials with different adhesive approaches, no difference was observed between "self-etch" and "etch-and-rinse" adhesives (Bitter et al. 2014b). Conflicting data exist concerning the performance of conventional resin cements (both self-adhesive or multi-step resin cements) and post-and-core materials with either better performance of a post-and-core material applied with an "etch-and-rinse" adhesive system (Mazzoni et al. 2009) or a "self-etch" adhesive system (Rodig et al. 2010) compared to conventional resin luting agents. Another study revealed no difference in bonding performance between post-and-core materials and conventional resin cements to aged tribochemical-coated posts (Schmage et al. 2012). The same working group also demonstrated for untreated posts (Schmage et al. 2009a) and exactly fitting posts (Schmage et al. 2009b) no significant differences in pull-out force between core materials and conventional resin luting agents although differences between core materials had been observed.

Only one clinical study is available testing whether simultaneous post luting and core buildup using one material or the use of a separate self-adhesive resin cement for post luting affect the clinical outcome (Juloski et al. 2014). After an observation period of 4 years, the luting material did not influence the failure risk of the endodontically treated teeth. Further in vivo and in vitro studies are mandatory to investigate the long-term clinical performance of simultaneous post luting and core buildup using one material before general recommendations can be given. Nevertheless, the use of these materials appears to be promising.

9.4 Conclusion

Bonding to root canal dentin is still a challenge especially because of the high C-factor when luting fiber posts, the visual limitations inside the root canal, and the challenging characteristics of root dentin as a bonding substrate. Furthermore, after root canal filling and post space preparation, the root canal walls are usually coated with remnants of sealer and gutta-percha as well as smear layer and debris that could hamper adhesion inside the canal. Consequently, cleaning of the post space using higher magnification for visualizing the post space is indispensable, and the adhesive procedure inside the root canal will benefit the most from a perfect clean root dentin surface that is not contaminated with any kind of sealer.

Mechanical cleaning using hand instruments or files of the post space preparation should be combined with a final irrigation protocol using 1 % NaOCl applied with passive ultrasonic activation followed by distilled water. This procedure can be recommended for smear layer removal after post space preparation irrespective of the adhesive strategy. Further irrigation using 99 % ethanol has been suggested to improve the long-term bonding performance for adhesively luted fiber posts, and promising results could be achieved. However, the effects of ethanol pretreatment seem to depend on the composition of the adhesive system used, and therefore, more research on this field is required until final recommendation can be given.

Various pretreatment procedures of the fiber post surface were tested to enhance fiber post bonding. The effects of the pretreatment procedures were strongly dependent on the micromorpholgy of the post surface and the composition of the matrix as well as on the resin luting agent used. Aggressive pretreatment procedures such as sandblasting, Cojet treatment, or application of hydrofluoric acid may damage fibers and possibly affect post integrity and should therefore be avoided. Improved wetting of the post surface as well as compatibility between resin luting agent and matrix of the post seem to be important factors for optimal fiber post bond strength.

Invasive post space preparation should be avoided because of substance loss and modification of the natural root canal geometry that might affect the fracture resistance of root canal-treated teeth. Perfectly fitting posts that result in small resin cement layer thickness are not necessarily required; moreover, some studies rather describe negative effects on bond strength of perfectly fitting posts. Conflicting results exist with respect to the adhesive strategy that can be recommended for bonding fiber posts. Besides a high heterogeneity among studies, no difference in bond strength between “self-etch” and “etch- and-rinse” adhesives in combination with a regular resin cement inside the root canal could be observed, and results appeared to be more product dependent than affected by the adhesive approach. Evidence exists that fiber post bonding was more reliable when using self-adhesive resin cements. However, the clinical procedure is facilitated when simultaneous post luting and core buildup using one material is performed and data of testing these materials also appeared to be promising although no final recommendations can be given.

The appearance of inhomogeneities inside the cement layer of adhesively luted fiber posts has been often described in the literature (Perdigao et al. 2007b; Sterzenbach et al. 2012b). However, the effect of the occurrence of voids inside the cement layer remains controversial. Application aids specially designed for the root canal have been shown to be beneficial with respect to a reduced occurrence of voids inside the cement layer (Watzke et al. 2008; Watzke et al. 2009) and can therefore be recommended.

9.5 Summary

The following clinical relevant points should be considered for adhesive luting of fiber posts:

- High C-factor, visual limitations and remnants of sealer, gutta-percha, and smear layer challenge adhesive procedure inside the root canal.
- Adhesive procedure benefits the most from a perfect clean root dentin surface.
- Passive ultrasonic activation of 1 % NaOCl is recommended as final irrigation prior post placement irrespective of adhesive strategy.
- Final irrigation can be completed by using ethanol 99 % in order to improve long-term bonding performance of adhesively luted posts.
- Aggressive pretreatment procedures of the fiber post surface such as sandblasting, Cojet, or hydrofluoric acid should be avoided.
- Improved wetting of the fiber post surface and compatibility between resin cement and matrix of the post are important for fiber post adhesion.
- Invasive post space preparation should be avoided.
- Preservation of sound tooth structure is important for long-term survival of endodontically treated teeth.
- Perfectly fitting posts are not required, and large resin cement layer thickness does not necessarily hamper fiber post retention and restoration stability.
- Fiber post bonding is more reliable when using self-adhesive resin cements.
- Application aids specially designed for the root canal have been shown to be beneficial with respect to a reduced occurrence of voids inside the cement layer.

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Provisional Restorations

10

Jorge Perdigão and George Gomes

Abstract

Teeth prepared for partial or full-coverage restorations must be protected and stabilized with provisional restorations that reproduce the form and function of the final restoration. Provisional treatment may also provide an important tool for the management of patients, as a common perception of the treatment outcome and respective limitations can be identified. It is therefore imperative to fabricate high-quality provisional restorations to achieve a successful treatment. This chapter will focus on current materials for provisional restorations, their advantages and limitations.

10.1 Introduction

According to The Academy of Prosthodontics (2005), an "*interim restoration is a fixed or removable dental prosthesis, or maxillofacial prosthesis, designed to enhance esthetics, stabilization and/or function for a limited period of time, after which it is to be replaced by a definitive dental or maxillofacial prosthesis. Often such prostheses are used to assist in determination of the therapeutic effectiveness of a specific treatment plan or the form and function of the planned for definitive prosthesis – Synonyms – PROVISIONAL PROSTHESIS, PROVISIONAL RESTORATION*."

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The fabrication of excellent provisional restorations is crucial to the success of the definitive restoration, playing a determining role in the outcome of the overall treatment (Table 10.1) (Vahidi 1987; Gratton and Aquilino 2004). The prerequisites and expectations for provisional restorations are identical to those of definitive restorations, except for longevity. Nevertheless, provisional restorations must be strong enough to maintain their structural integrity, as they may be used during long periods of time while other treatments, such as a surgical crown lengthening procedure, are being finalized. In other instances provisional restorations are left in place for extended periods when questions subsist regarding the restorability or the pulp vitality of a tooth.

Provisional restorations are essential as a diagnostic tool for testing out the changes in esthetics, position, contour, size, and occlusion, before they are incorporated in the definitive restoration (Zinner et al. 1989; Wassell et al. 2002; Hammond et al. 2009). Provisional restorations are also an excellent checking tool for the adequacy of tooth reduction. Therefore, provisional restorations have an essential role as a blueprint for the definitive restoration to foresee the ideal treatment outcome prior to carrying out the definitive rehabilitation (Fox et al. 1984; Luthardt et al. 2000). Additionally, highly esthetic provisional anterior restorations may make the patient more confident in the clinician's ability to perform the treatment.

10.2 Materials

There are many choices of materials for provisional restorations. For single-unit restorations, these choices include acrylic resin for custom-made provisional restorations, bis-acryl-based composite resin (bis-acryl), bisphenolA-diglycidyl-

Table 10.1 Rationale for provisional treatment

Protect pulpal tissue and sedate prepared abutments
Protect teeth from caries lesions
Provide comfort and function
Provide method for immediately replacing missing teeth
Prevent migration of abutments
Improve esthetics
Maintain or improve periodontal health
Reinforce the patient's oral home care
Assist with periodontal therapy by providing visibility and access to surgical sites when removed
Provide a matrix for the retention of periodontal surgical dressings
Stabilize mobile teeth during periodontal therapy and evaluation
Provide anchorage for orthodontic brackets during tooth movement
Aid in developing and evaluating an occlusal scheme before definitive treatment
Allow evaluation of vertical dimension, phonetics, and masticatory function
Assist in determining the prognosis of questionable abutments during prosthodontic treatment planning

methacrylate (bis-GMA)-based composite resin, prefabricated polycarbonate crowns, metal crowns, celluloid crown forms, composite resin crowns, and direct composite resin. For FPDs, acrylic resins, bis-acryl or bis-GMA automix composite materials, or laboratory-fabricated resin shells are preferred.

The selection of materials for provisional restorations is based on their mechanical and physical properties, as well as their biocompatibility (Duke 1999). Materials for provisional restorations are classified using several different criteria. Some authors have suggested using chemical composition, which divides these materials into methacrylates and composite resins.

Anterior provisional restorations usually have more complex esthetic demands than those desirable for the posterior region (Sham et al. 2004). These esthetic requirements have become more relevant within the past years as a result of patients being more aware of dental esthetics. Provisional restorations in single anterior crowns do not require high resistance to compression. On the other hand, the materials used for provisional restorations in long-span FPDs must provide greater tensile strength as opposed to those used for single units (Koumjian and Nimmo 1990). Long-term provisional restorations require materials that are more durable (Amet and Phinney 1995). The requirements for materials used in provisional restorations are displayed in Table 10.2.

Table 10.2 Requirements for provisional restorations

Biological	Preserve pulpal health (excellent sealing)
	Non-irritating to pulp and other tissues
	Low exothermicity
	Minimal residual monomer
	Maintain periodontal health, promote guided tissue healing
	Physiological emergency profiles and embrasures
	Do not hinder routine at-home oral hygiene
Physical/mechanical	Dimensionally stable, nonporous
	Mechanically strong and durable
	Good marginal adaptation
	Low thermal conductivity
	Excellent handling (ideally automix), short setting time
	Easy to remove without damaging the tooth
Esthetic	Esthetically acceptable with variety of shades; toothlike appearance
	Serve diagnostic purposes for esthetics
	Good polishability, stain resistant
Functional	Provide and maintain stable occlusal relationships
	Have adequate proximal contact to avoid shifting after the final impression is taken
	Serve diagnostic purposes for occlusion
	Easy to repair or remake
Other	Inexpensive
	Odorless
	Easy to implement infection control measures

Provisional restorations are usually made using different techniques: (1) *custom fabrication* and (2) *fabrication with preformed materials*. These procedures can be accomplished with direct techniques in the clinic, indirect laboratory techniques, or direct/indirect combined techniques (Vahidi 1987). While indirect techniques may involve laboratory costs and increased time for fabrication, custom fabrication has been known to be the best choice for provisional restoration fabrication (Christensen 1996).

10.2.1 Materials for Custom-Fabricated Provisional Restorations

Custom fabrication allows for intimate contact between a provisional restoration and prepared tooth. The most common materials used for custom-made provisional restorations are (1) polymethyl methacrylate (PMMA) resin, (2) polyethyl methacrylate (PEMA) resin, (3) bis-acryl resin, (4) urethane dimethacrylate (UDMA) resin, and (5) Bis-GMA resin (Krug 1975; Lui et al. 1986; Vahidi 1987; Wassell et al. 2002; Strassler 2009). PMMA- and bis-acryl-based temporary restorations are currently the most popular materials.

Acrylic materials are the oldest materials currently in use. Auto-polymerizing acrylic-based materials are easy to use to fabricate provisional restorations and easily fill in the shape defects, allowing for a simple and quick manipulation. Among their disadvantages, the most important are their significant polymerization shrinkage, a short working time, an unpleasant odor, and a pronounced exothermic setting reaction, which may injure the dental pulp (Grajower et al. 1979; Michalakis et al. 2006; Chen et al. 2008). Residual methacrylate monomer may trigger cytotoxicity and potential allergic reactions (Lee et al. 2002; Lai et al. 2004).

Acrylic resin provisional materials typically refer to two different chemical materials, PEMA and PMMA. There are other acrylic resins for provisional restorations, but the authors will refer to the two most commonly used acrylic resins in this chapter.

10.2.1.1 Polymethyl Methacrylate (PMMA)

PMMA-based materials were introduced in the 1940s and have been the preferred material for fabricating provisional restorations with the direct and indirect techniques (Kaiser and Cavazos 1985; Duke 1999; Burns et al. 2003; Christensen 2004). Auto-polymerizing PMMA-based resin is available in various shades as a powder and liquid formulation. PMMA-based provisional restorations have a long record of use, low cost, acceptable marginal adaptation (Wang et al. 1989; Duke 1999; Christensen 2004), and high mechanical strength compared to other methacrylate resins (Wang et al. 1989). However, PMMA has a low abrasion resistance, which leads to wear of the material over time (Vallittu et al. 1994).

Achieving optimal esthetics with PMMA-based resin can be difficult and time-consuming. This material has poor color stability and poor surface texture/porosity (Luthardt et al. 2000; Bidra and Manzotti 2012), which might be the reason why

Table 10.3 Examples of materials for custom-fabricated provisional restorations

Material	Commercial name	Manufacturer
PMMA resin	Alike	GC America
	Trim Plus	Harry J. Bosworth Company
	Jet Set-4	Lang Dental Manufacturing, Co
	Unifast LC	GC America
PEMA resin	Trim	Harry J. Bosworth Company
	Trim II	Harry J. Bosworth Company
	Snap	Parkell
	Splintline	Lang Dental Manufacturing, Co
UDMA composite resin	Revotek LC	GC America
	Triad VLC Provisional Material	Dentsply
Bis-GMA composite resin	TempSpan	Pentron Clinical
Bis-acryl composite resin	Access Crown	Centrix
	Cool Temp Natural	Coltene
	Integrity	Dentsply
	Luxatemp Solar	DMG America
	Protemp Plus or Protemp 4	3M ESPE
	Structur	VOCO
	Telio CS C&B	Ivoclar Vivadent
	Temphase	Kerr
	Ultra-Trim	Harry J. Bosworth Company

Bis-GMA bisphenol A diglycidyl-methacrylate, *PEMA* polyethyl methacrylate, *PMMA* polymethyl methacrylate, *UDMA* urethane dimethacrylate

esthetics is still problematic with these resins. Some authors have suggested the use of a surface liquid polish coating to prevent biofilm formation by preventing protein adsorption (Davidi et al. 2008). Other materials, such as polycarbonate crowns and bis-acrylic resins have been suggested in lieu of acrylic resins (Bidra and Manzotti 2012).

The temperature increase during polymerization of PMMA is significantly higher than those of polyvinyl ethyl methacrylate, light-cured urethane dimethacrylate, and bis-acryl resins (Lieu et al. 2001). The intra-pulpal temperature rise associated with the polymerization of PMMA-based materials could be up to five times that associated with the normal consumption of thermally hot liquids (Plant et al. 1974). The use of PMMA in fabricating provisional restorations should be discouraged when the direct technique is used. However, when provisional restorations are made using the indirect technique, PMMA is a good option owing to its superior physical properties (Kaiser and Cavazos 1985). Some of the commercially available PMMA materials are displayed in Table 10.3.

10.2.1.2 Polyethyl Methacrylate (PEMA)

PEMA-based materials for provisional restorations were introduced in the 1960s and have a number of advantages and disadvantages relative to PMMA-based materials. One study showed a higher fracture resistance relative to PMMA and bis-acryl materials (Osman and Owen 1993). PEMA has been considered a good option for direct provisional restorations for short-term use (Vahidi 1987; Christensen 1996). Some of the commercially available PEMA-based materials are shown in Table 10.3.

10.2.1.3 Composite Resins

Bis-Acryl

The introduction of bis-acryl composite resin was aimed at overcoming the shortcomings of methacrylates. It has been reported that bis-acryl resins used for provisional restorations have advantages over other resin-based provisional materials (Table 10.4).

Bis-acryl-based composite resin, a hydrophobic material similar to Bis-GMA-based composites, is available in a two-paste automix delivery system. Bis-acryl resin-based materials are easy to use but are expensive compared to other materials for custom-made provisional restorations. They also exhibit low polymerization shrinkage, leading to a good marginal fit and good transverse strength (Strassler et al. 2007). The presence of a thick oxygen inhibited layer on the surface upon setting makes them less stain resistant compared to methacrylates but easier to repair using flowable composites (Hagge et al. 2002; Bohnenkamp and Garcia 2004). While bis-acryl-based materials exhibit enhanced microhardness and resistance to wear over PMMA (Diaz-Arnold et al. 1999; Strassler et al. 2007), they are more brittle. Bis-acryl composites can be polished using the same polishing points used for direct restorative composite materials. The resulting surface texture depends on the filler particle size (Fig. 10.1).

Comparing bis-acryl and PMMA materials in terms of occlusion, contour, marginal fidelity, and finish, bis-acryl materials were significantly superior to PMMA for both anterior and posterior teeth (Solow 1999; Young et al. 2001). The use of bis-acryl resin in a polyvinyl siloxane impression matrix significantly reduced temperature increases in the pulpal chamber compared with those obtained when bis-acryl resin was used in vacuum-formed polypropylene matrix (Castelnuovo and

Table 10.4 Advantages of bis-acryl resins*

Filled composite resins, therefore they are harder, more resistant to dietary solvents, and more resistant to occlusal wear than unfilled acrylic resins
Quick and easy to use
Set rapidly and can be removed from the mouth after 60–75 s
Flexible to make insertion and removal easier
Low elastic modulus to withstand occlusal forces
Undergo minimal polymerization shrinkage
Minimal heat from polymerization, do not cause thermal damage to the pulp
Radiopaque
Can be easily repaired with a flowable composite resin
Excellent color stability and stain resistance
Little odor when mixed

*From Hagge et al. (2002), Gratton and Aquilino (2004), Strassler (2009)

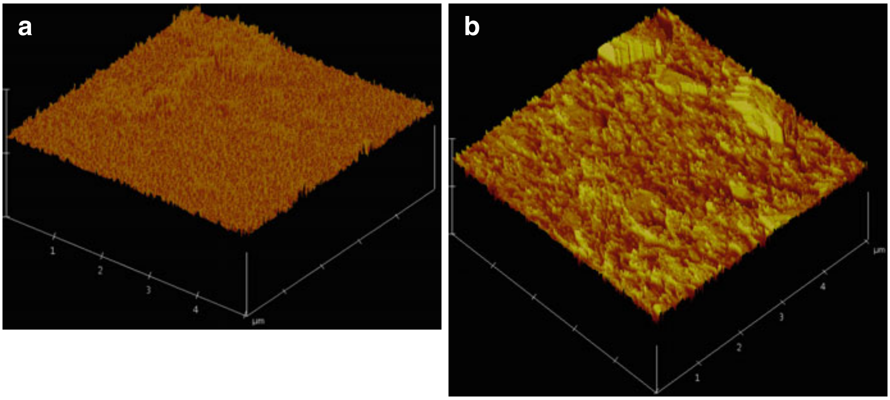

Fig. 10.1 Atomic force microscope images of bis-acryl composite resins polished with Sof-Lex (3M ESPE) disks of decreasing abrasiveness. The field dimensions are 5 μm × 5 μm. (**a**) Protemp Plus or Protemp 4 (3M ESPE). (**b**)Structur (VOCO)

Tjan 1997). Table 10.3 displays some bis-acryl-based composite resins currently available.

> This material is currently the top choice for provisional restorations in many private dental practices and dental schools in the USA.

UDMA

Light-cured resin-based materials for provisional restorations, such as urethane dimethacrylate (UDMA)-based resins, were first introduced in the 1980s (Emtiaz and Tarnow 1988). Some of these materials contain filler, such as silica particles, to improve physical properties such as reduced polymerization shrinkage (Passon and Goldfogel 1990). Light-cured UDMA-based resins do not leave residual monomers as PMMA does, the reason why they exhibit significantly decreased tissue toxicity (Khan et al. 1988). These materials are less expensive and time-consuming than laboratory-made provisional restorations and other materials used for direct provisional restorations (Haddix 1988). Besides, they are adaptable intraorally because of their putty-like consistency and are repairable with flowable composites. However, UDMA-based materials for provisional restorations do not result in good marginal fidelity compared to bis-acryl- and PEMA-based materials (Tjan et al. 1997). Light-cured UDMA-based materials are brittle, which makes them contraindicated for high strength posterior restorations (Prestipino 1989). For anterior restorations, they are not as stain resistant as other materials and are available in limited shades. Examples of UDMA-based materials currently available for use are displayed in Table 10.3.

Bis-GMA

Dual-cured resin materials for provisional restorations are also available (Table 10.3). An example is TempSpan (Pentron Clinical), which is carried into the mouth in a

Table 10.5 Materials for CAD/CAM-generated provisional restorations (Güth et al. 2013; Keul et al. 2014)

Commercial name, manufacturer	Composition
artBloc Temp, Merz Dental	Unfilled PMMA
Telio CAD, Ivoclar Vivadent	Unfilled PMMA
Telio CAD for Zenotec, Wieland Dental	Unfilled PMMA
Cercon base PMMA, Dentsply	Unfilled PMMA
VITA CAD-Temp, VITA Zahnfabrik	PMMA, 14 % micro-filler fillers
polycon ae, Straumann	Highly cross-linked PMMA (IPN, interpenetrated polymer network)
New Outline, Anaxdent	Unfilled PMMA
Quattro Disc eco PMMA, Goldquadrat	Unfilled PMMA

clear vinyl polysiloxane putty matrix (TempSpan Clear Matrix Material, Pentron Clinical). Compared to methacrylate-based materials, Bis-GMA resins have good marginal fit, excellent polishability, low polymerization shrinkage, and minimal exothermic reaction and are repairable with flowable composites. As with all resin-based materials, Bis-GMA resins more expensive than methacrylate-based materials.

10.2.1.4 Materials for CAD/CAM

Highly esthetic provisional restorations can now be milled out of high-density PMMA monolithic blocks using CAD/CAM technology (Table 10.5). These restorations are precision milled to fit single- and multi-unit preparations, offering increased strength. There are several drawbacks of this new technology. One drawback is cost, as the impression must be sent to a laboratory for the provisional restoration to be fabricated prior to the clinical procedure.

The variation in light transmission is wide among brands. The total transmission values varied from 33.1 to 54.5 % in a recent study that included 11 CAD/CAM PMMA blocks (Güth et al. 2013). Another study found that CAD/CAM resins have a lower wear rate than resins polymerized manually. However, CAD/CAM resins showed higher wear values than glass-ceramic, with the exception of Telio CAD (Ivoclar Vivadent) (Stawarczyk et al. 2013).

10.2.2 Materials for Preformed Provisional Restorations

Preformed provisional crowns or matrices usually consist of tooth-shaped shells of polycarbonate resin, PMMA resin, celluloid, or metal. They are adapted to the preparation by relining them with acrylic resin to provide a tight fit, but they usually need considerable margin adjustments as well as occlusal reduction. They are commercially available in various tooth sizes and are usually selected for a particular tooth anatomy. Nonetheless, available sizes and contours are limited. Compared with custom-fabricated restorations, this treatment method is fast but is more likely to result in an inadequate outcome. This can result in ill-fitting provisional restorations (Christensen 1996). For minor discrepancies, the “bead-brush” technique or a flowable composite may be used (Hammond et al. 2009).

10.2.2.1 Clear Celluloid Crown Forms

Clear celluloid crown forms are made from a thin shell of cellulose acetate (Strassler 2009). Crowns Forms (Dentsply), Full Forms (Directa AB), and Odus Pella Transparent Crown Forms (Moore Co.) are some of the commercial names. They can be filled with acrylic resin or with composite resin after they are trimmed and adapted to the gingival margin.

10.2.2.2 Tooth-Colored Resin Crowns

Polycarbonate resin crowns have long been used in prosthodontics to fabricate provisional restorations for single-unit restorations (Bidra and Manzotti 2012). These crowns are reinforced with microfibers to strengthen their structure and improve esthetics. As with other preformed crowns, they fit poorly and must be relined with acrylic resin. Final adjustments of margins and occlusal contacts may be time consuming (Gratton and Aquilino 2004). Polycarbonate resin crowns have a number of superior properties compared to PMMA-based materials, including color stability, abrasion resistance, hardness, esthetics, and mechanical strength (King et al. 1973; Federick 1975; Bidra and Manzotti 2012). Practitioners commonly use polycarbonate resin shell crowns as a matrix material around a prepared tooth that is relined with acrylic resin to customize the fit. Among others, the two most common polycarbonate crowns are made by 3M ESPE and by Directa AB.

PMMA resin crowns, such as GC Crowntek (GC America), are also available. As with polycarbonate crowns, PMMA preformed crowns can be relined with PMMA- or PEMA-based resin.

10.2.2.3 Metal Crowns

Aluminum There are two major aluminum-based provisional crowns available, Aluminum Shell Crowns (Miltex) and Golden Anodized Crowns (3M ESPE). Aluminum-based crowns provide quick tooth adaptation due to the softness and ductility of the material, but this same positive quality may result in rapid wear that leads to perforation in function and/or extrusion of teeth (Lui et al. 1986). An unpleasant taste is sometimes associated with aluminum materials.

Tin Tin Crowns (Directa AB) are made of tin, whereas Iso-Form Crowns (3M ESPE) are made of tin-silver. Like aluminum, they possess reasonable ductility and can be contoured quickly, but the occlusal table is reinforced so they are more resistant to wear (Lui et al. 1986) than aluminum crowns. They are indicated for short-term provisional restorations in the posterior area and can be used as a template for a tooth-colored provisional restoration.

Stainless steel For longer-term use, stainless steel crowns are available (Stainless Steel Permanent Molar Crowns, 3M ESPE), but may be more difficult to adapt to a prepared tooth because they are harder and lack ductility compared to the other two types of metal crowns.

Metal provisional materials are generally esthetically limited to posterior restorations.

10.2.2.4 Protemp™ Crown

The Protemp Crown Temporization Material (3M ESPE) is a preformed malleable bis-GMA-based composite resin used as provisional crown for single-unit temporization of posterior teeth and canines (Fig. 10.2). The crown size is selected and trimmed with scissors to achieve the proper height. Once it is molded to the preparation with composite instruments and contacts established, the patient is instructed to bite on the crown to achieve adequate occlusion. The crown is then light-cured for 2–3 s from occlusal, buccal, and lingual surfaces. The provisional restoration is then removed, light-cured for 1 min, and finished with a carbide bur and polishing points prior to cementation. The margins may be modified using a flowable composite. It combines the advantages of composite resins (good polishability, esthetics, wear resistance, marginal fit) with those of prefabricated provisional crowns, such as ease of use, easy clean-up, and no need for a template matrix (Strassler 2009). The Protemp Crown is currently available in universal shade.

10.3 Provisional Luting Materials

While it is required that they allow for an easy removal of the provisional restoration, it is very crucial that these luting agents provide good *marginal sealing* to prevent pulpal irritation in a vital tooth or reinfection of the root canal environment in an endodontically treated tooth. Provisional luting agents should have good mechanical properties, low solubility, and tooth adhesion to resist bacterial penetration and their by-products (Baldissara et al. 1998). The most common luting materials used for provisional purposes include (1) calcium hydroxide cement, (2) zinc-oxide eugenol cement, and (3) eugenol-free zinc-oxide cements (Baldissara et al. 1998). Polycarboxylate cement, indicated for definitive restorations, may be used with provisional restorations when the preparation is not ideal, such as in short preparations or those with excessive draw (Wassell et al. 2002). Polycarboxylate cements bond chemically (Tyas and Burrow 2004) to calcium in enamel and dentin, which provides a better seal than other cements used for provisional restorations.

Provisional luting materials have poor mechanical properties that tend to deteriorate over time.

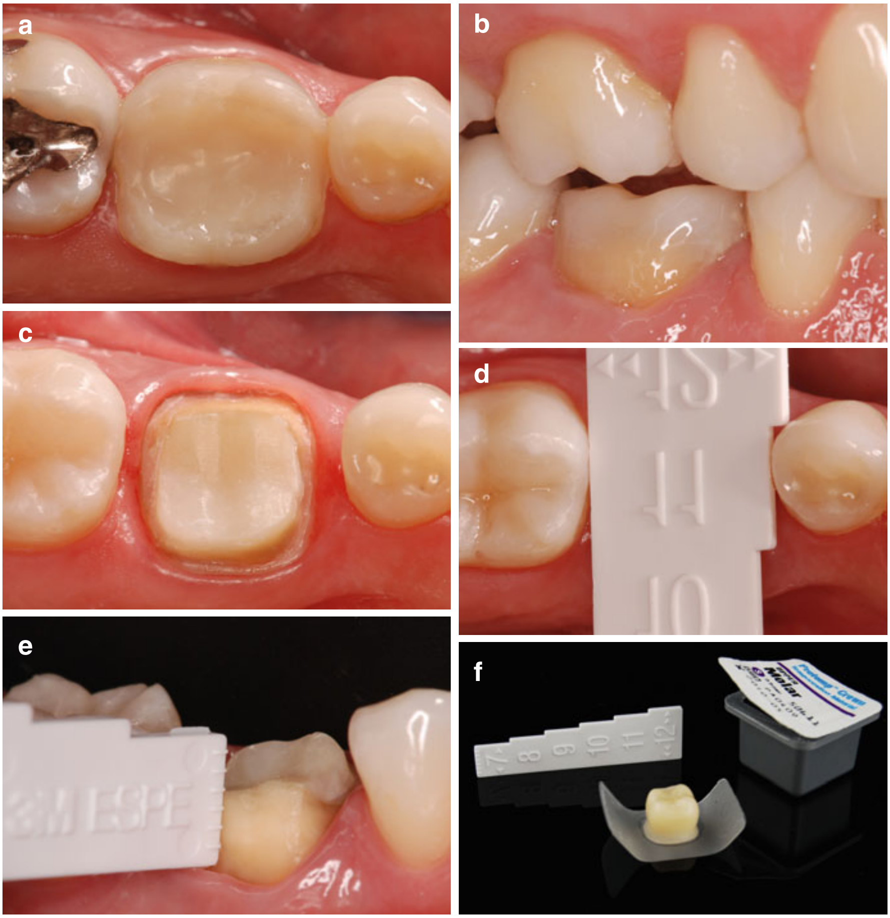

Fig. 10.2 Clinical sequence showing a provisional restoration made with Protemp Crown Temporization Material (3M ESPE). (**a**) Preoperative view of an endodontically treated mandibular first molar restored with composite-build-up composite resin. (**b**) Buccal view. (**c**) Tooth was prepared for a monolithic zirconia crown. (**d**) The approximate mesial-distal width was determined using the Protemp Crown Size Tool. (**e**) The same tool was used to measure the approximate crown height. (**f**) The Protemp Crown size corresponding to the measurements was selected. (**g**) The Protemp Crown was trimmed with scissors. (**h**) The provisional crown was adapted to the slightly moist prepared tooth. (**i**) Patient was asked to gently close. The buccal surface was adapted with a composite instrument, and the restoration was tack-cured from the buccal aspect for 3 s. The lingual and occlusal surfaces were then adapted and tack-cured for 3 s. (**j**) The Protemp Crown was gently removed from the preparation and light-cured for 40 s from each surface. (**k**) The provisional crown was tried in and occlusion adjusted. (**l**) Finishing was carried out with carbide finishing burs, Sof-Lex (3M ESPE) disks and PoGo finishing points (Dentsply). (**m**) After the impression was taken, the provisional restoration was cemented with Temp-Bond NE (Kerr Co.) and excesses removed. (**n**) Buccal view of provisional restoration. (**o**, **p**) A monolithic zirconia crown was fabricated in the dental laboratory. (**q**) The intaglio surface was sandblasted with aluminum oxide particles. (**r**) The definitive restoration was cemented with a self-adhesive resin cement. (**s**, **t**) Postoperative view

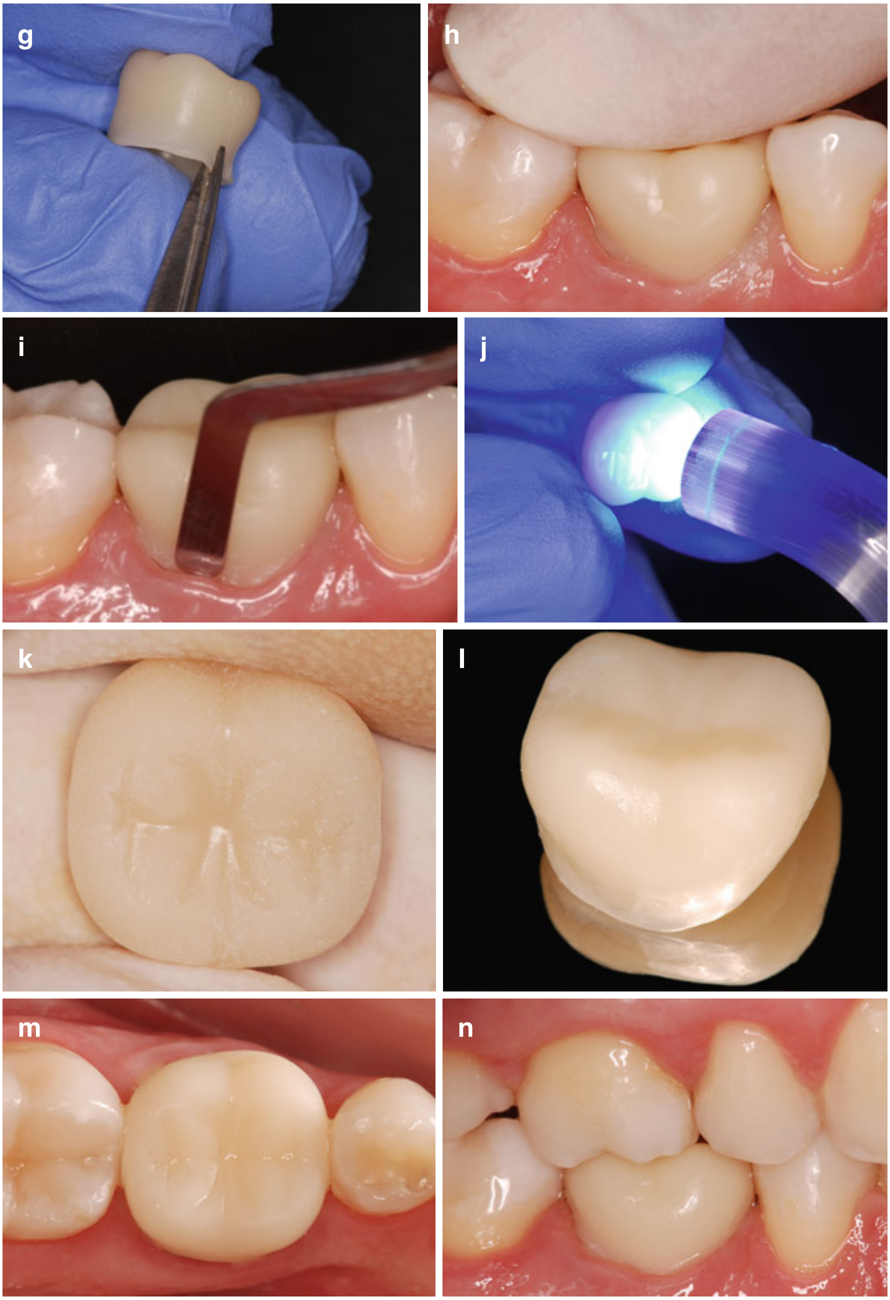

Fig. 10.2 (continued)

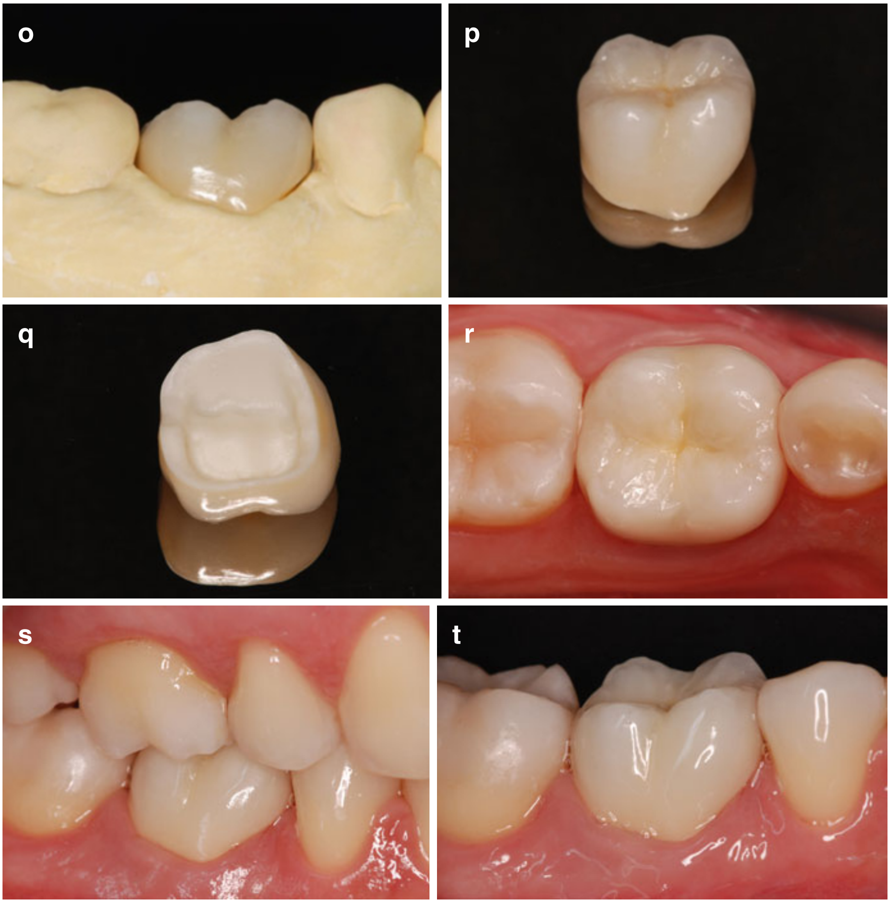

Fig. 10.2 (continued)

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Cast Dowel and Core

11

WookJin Seong

Abstract

The cast dowel and core (D&C) technique has been used for a long time and still being used today when prefabricated fiber post prevails. Several in vitro and in vivo studies have shown that prefabricated fiber posts and core build-ups are doing better or similar to cast D&Cs. However, the comparison between prefabricated fiber posts and cast D&Cs should be done fairly in terms of the amount of remaining tooth structure, cementation/bonding techniques used, and clinical expertise of the researchers, among others. This chapter will focus on (a) the indications for cast D&Cs over the prevalent prefabricated fiber posts and composite core build-ups, (b) factors affecting the long-term success of cast D&Cs, (c) two different clinical techniques (direct pattern and indirect impression) and respective sequences to fabricate a cast D&C and subsequent full-coverage restoration, and (d) the cementation/bonding of cast D&Cs as well as the full-coverage restoration.

11.1 Introduction

The concept of a dowel to help retain a crown on a compromised tooth has been around for more than two centuries. Pierre Fauchard used a wooden post jammed into the root canal space to retain a crown in the eighteenth century (Prothero 1921). Many different designs of dowels as an integral part of the crown have emerged and disappeared. With the increased interest in the restoration of the pulpless tooth, a dowel-core separate from the crown gradually replaced the one-piece dowel crown (Shillingburg and Kessler 1982). Even after prefabricated metal posts have appeared

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with the combination of amalgam and composite core materials, one-piece cast dowel and core (D&C) has served as a standard of the root canal treated tooth restoration. The recent surge of fiber posts and strong composite core build-up materials and composite resin bonding techniques has replaced cast D&Cs gold standard status due to the fiber post's predictable clinical performances and convenience to both patient and practitioners. In this chapter, the current role of cast D&C against the popular fiber post and composite core build-up system will be discussed.

11.2 Indication of Cast Dowel and Core

To be able to fabricate a cast D&C direct pattern and cement a cast D&C, no gross undercuts should be present throughout the passage of cast D&C, orifice of root canal, pulp chamber, and internal axial walls of clinical crown. If a cast D&C is planned in an endodontically treated tooth with existing multiple axial walls, unnecessary tooth structure has to be removed to create a reasonable path of insertion for a cast D&C or large gap between the tooth structure, and a cast D&C should be filled by the cement. In both incidences, overall strength of the cast D&C restored system will be compromised. Many clinical studies showed that the amount of the remaining sound tooth structure has a significant effect on the survival of post and core restorations, suggesting to keep as much of sound tooth structure as possible to enhance the prognosis of the restoration (Creugers et al. 2005; Ferrari et al. 2007, 2012). Therefore, a cast D&C should only be considered when there is a limited amount of tooth structure present (such as one wall or less with/without ideal ferrule) where the cast D&C can be fabricated without unnecessary tooth structure reduction from the pulp chamber and/or internal axial walls of clinical crown.

To make a fair comparison of study outcomes between prefabricated fiber post and cast D&C, additional efforts are necessary on whether cohorts (prefabricated fiber post vs. cast D&C) of each study were in similar conditions in terms of remaining tooth structure, cementation/bonding techniques used, and clinical expertise of the researchers, etc. Many of the early prefabricated metal post studies were excluded because better-performing fiber post has basically replaced prefabricated metal post since its introduction in 1989. No randomized controlled trials (RCT) comparing cast D&C and prefabricated fiber post were found either in a 1993 meta-analysis (Creugers et al. 1993) or in a 2002 systematic review (Heydecke and Peters 2002). Only one RCT comparing cast D&C and prefabricated fiber post was found both in a 2007 Cochrane review (Bolla et al. 2007) and a 2009 systematic review (Theodosopoulou and Chochlidakis 2009). The Cochrane review noted that the RCT published in 2000 by Ferrari et al. (2000) was at high risk of bias and concluded that more RCTs are needed to confirm whether fiber-reinforced post and core systems are superior to the cast D&C.

This RCT by Ferrari et al. included 200 endodontically treated teeth with severe loss of tooth structure in 200 patients, and outcomes of cast D&C and Composipost system (carbon fiber post) were evaluated after 4 years of clinical service (Theodosopoulou and Chochlidakis 2009). The Composipost had 2 % failure (all were endodontic failures), while the cast D&C had 14 % failure (9 %, root fracture; 2 %, crown dislodgement; 3 %, endodontic failure). Even though authors stated that 200 teeth were randomly divided into two groups, there was no further description of blindness of investigators from randomization and outcome evaluation. Also, authors did not define the inclusion criteria for severe tooth loss and did not quantify the remaining tooth structure of 200 teeth before the random assignment. The carbon fiber posts were bonded with multistep etch-and-rinse adhesive and a dual-cured resin cement, while the cast D&C was cemented with zinc phosphate cement. Since all 200 patients were enrolled during a 6-month period, multiple clinicians might have performed the clinical procedures. No further description of D&C length and width in nine root fracture cases was given but authors speculated that high numbers of root fracture could be due to stress concentration in uncontrolled area of root and the fact that cast D&C retention was achieved from the friction along the root walls. With careful planning and skillful execution of the canal preparation and cast D&C fitting by experienced practitioners, both of the speculated causes should not have happened if the cast posts had passive fit and their lengths were as long as possible while a 4–5 mm apical seal was maintained.

Recently, several small short-term RCTs comparing cast D&C and fiber post have been published (Ferrari et al. 2000; Preethi and Kala 2008; Zicari et al. 2011). The sample size varied from 30 to 205 teeth over the 1–3-year follow-up period. All of them had very limited failures and concluded that both cast D&C and fiber post showed similar clinical performances. One 3-year follow-up of a RCT published in 2014 included only teeth with 0.0–0.5 mm ferrule height, with 72 teeth randomly assigned to cast D&C or fiber post (Zicari et al. 2011). Both fiber post and cast D&C were cemented with resin cement, and procedures were performed by undergraduate and graduate students who finished 12 h of lecture and training. Only four failures in total over the 3 years occurred, and survival rates of fiber post and cast D&C were statistically similar (91.9 % and 97.1 %, respectively). Two fiber posts debonded, and one fiber post induced root fracture in a premolar. One cast D&C induced root fracture in a molar.

Since there are still too few clinical studies comparing cast D&C and fiber posts, other clinical studies focusing on either fiber post or cast D&C alone were also reviewed. A retrospective study on 985 fiber posts reported 8 % failure rate over the 7–11 years of service (Ferrari et al. 2007). The endodontic failure was most with 39 cases, followed by 21 post debondings and 17 crown dislodgements. Authors reported that those mechanical failures were always related to the lack of coronal tooth structure. In other words, higher failure of the fiber post system is expected when there is limited amount of residual tooth structure such as one wall or less and/or absence of ideal ferrule. A 6-year RCT on 360 endodontically treated premolars showed 29–78 % success rates of two different types of fiber posts in three different extent of limited remaining tooth structure (one wall, only ferrule, no ferrule) (Ferrari et al. 2012). In these three limited tooth structure situations (one wall, only ferrule, no ferrule), the success rate of fiber posts was significantly lower than in the situations with enough tooth structure (two to four walls). The failure modes in these three limited tooth structure situations included post debonding, post/core fracture, crown dislodgement, endodontic failure, and root fracture.

A 5-year RCT including 319 cast metal D&C restorations performed by 18 operators reported an overall 96 % survival rate over the 5-year period (Creugers et al. 2005). If the cases of cast D&C used in minimum ferrule height teeth are isolated, three failures (three dislodgements of cast D&C) occurred out of 58 cases (94.8 %) over the 5-year period. Several earlier clinical studies of cast D&C show favorable success rates: 91 % on 96 posts over 6 years (Sarkis-Onofre et al. 2014), 92 % on 516 posts over 4.8 years (Bergman et al. 1989), 85 % on 456 posts over 6 years (Mentink et al. 1993), and 100 % on 27 posts over 10 years (Torbjörner et al. 1995).

A meta-analysis comparing fracture resistance between cast posts and fiber posts found 13 in vitro studies and indicated that the cast post group displayed significantly higher fracture resistance than the fiber post group (Ellner et al. 2003). The fracture mode of cast D&C had catastrophic failures, such as oblique or horizontal fracture in middle third of root or vertical fracture, while fiber post failures were repairable, such as fractures at the cervical third of roots or the cores. Study postulated that similar elastic modulus of fiber post to root dentin and thick resin cement between fiber post and root dentin working as a stress absorption layer might reduce the risk of root fracture compared to hard, well-fitting cast posts. Even though fracture modes of cast posts may be catastrophic, the fracture resistance of the system restored with cast posts can be significantly higher than that of fiber posts when canal preparation and post length/width are well controlled as seen in in vitro studies.

In summary, because studies show that keeping sound tooth structure is best for the long-term success of the endodontically treated tooth restoration, it is discouraged to remove sound tooth structure just to eliminate undercuts so that cast D&C can be fabricated. Therefore, cast D&C should be considered only when there is one wall or less with/without ideal ferrule present so that the cast D&C can be fabricated without unnecessary tooth structure reduction from the pulp chamber and/or internal axial walls of clinical crown.

As shown in many clinical studies, long-term restoration success rates of limited tooth structure of one wall or less with/without ferrule are not good, no matter prefabricate fiber post or cast D&Cs are used. Therefore, clinicians should approach cast D&C therapy as a final attempt to restore the compromised endodontically treated tooth with careful planning and skillful execution. If cast D&C fails, extraction and implant or fixed partial denture restoration option should be considered to replace the failed tooth. Since cast D&C restoration will be the last attempt to save the compromised tooth, the whole procedure should aim at creating the strongest connections between root-luting cement-cast D&C-luting cement-crown to improve the longevity of the restored tooth, without worrying about the possible catastrophic failure mode of the restored tooth.

11.3 Factors Affecting the Long-Term Success of the Cast Dowel and Core

Failure modes of cast D&C include endodontic failure, root fracture, post debonding with/without tooth structure fracture, and crown dislodgement (Creugers et al. 2005). There are no reports of post fracture, no post and core junction fracture, and no core fracture because cast D&C is usually one-piece casting of gold alloy. Based on the abovementioned failure modes of cast D&C, the following factors were identified as determinants of the long-term prognosis of cast D&C restored endodontically treated tooth.

11.3.1 Remaining Sound Tooth Structure

There are numerous in vitro and in vivo studies showing the importance of remaining tooth structure as a determinant of long-term success of post and core restoration, both for cast D&C and for prefabricated fiber posts. A 5-year follow-up RCT with 319 cast and metal posts concluded that the factor "remaining dentin height" appeared to have a significant effect on the survival of post and core restorations (98 % ± 2 % survival for "substantial dentin height" vs. 93 % ± 3 % for "minimal dentin height") (Creugers et al. 2005). Recent in vitro studies combining laboratory tests with 3-D finite element analysis reported that the presence of a 2 mm ferrule (versus no ferrule) showed favorable stress distribution and significantly increased fracture resistance for endodontically treated teeth regardless of the post system, cast D&C, or prefabricated fiber post (Zhou and Wang 2013; Santos-Filho et al. 2014). Therefore, the efforts to keep as much of sound tooth structure as possible are very important by not performing unnecessary tooth structure removal when a cast D&C is used to support a full-coverage crown.

11.3.2 Length of Cast D&C

Since there is no chemical bonding between cement and cast posts, roughness and surface area, which influence mechanical retention, are key factors to ensure the retention of cast posts. It has been claimed that the use of a longer rather than a thicker cast post improves retention positively (Veríssimo et al. 2014). An in vitro study that tested the retentive strength of sandblasted tapered metal posts with three different lengths (9 mm, 12 mm, 15 mm) and apical diameters (0.5 mm, 0.9 mm, 1.1 mm) found that the retentive strength increased proportionally to the length as well as to the diameter of the posts (Shillingburg et al. 1970). In addition to sandblasting, roughening the dentinal walls using handheld diamond rotary instrument and the use of resin luting cements provided statistically significant increases in dowel retention (Nergiz et al. 2002). Since keeping adequate thickness of root dentin is very important to prevent root fracture with cast D&C, increasing cast post length as well as roughening post and dentin walls can be the most effective and safest way to maximize post retention.

Shorter cast posts have been believed to increase the prevalence of root fracture compared to longer posts (Fig. 11.1). A finite element analysis study using a mandibular premolar model reported that maximum shear stress was found at the cast D&C post apical area, which decreased with the increase of post length from 4 mm (90 MPa) to 10 mm (30 MPa) (Balbosh et al. 2005). Authors concluded that the bonding integrity

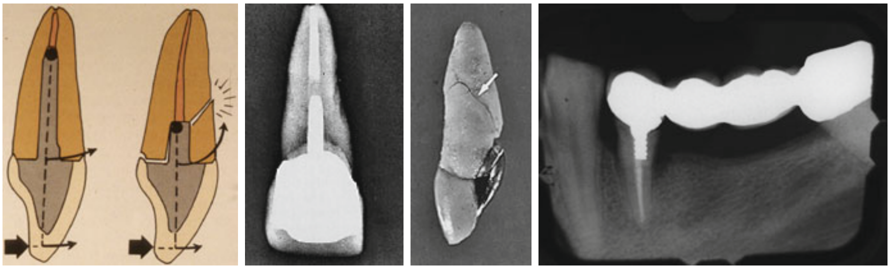

Fig. 11.1 Short post can induce stress concentration to the side of root dentin upon bending moment therefore can induce root fracture easily. The longer the post, the more evenly the forces are distributed over the length of the root therefore less chance for the root fracture is present

to the cervical area would play a critical role in the survival of the fiber post and composite core restored tooth, whereas for the cast D&C, the bond of the post to root dentin would be essential for the long-term survival. Another in vitro study combined laboratory tests with 3-D finite element analysis found that 7 mm long cast posts (compared to 12 mm long posts) recorded significantly lower fracture resistance values and produced higher rates of root fractures (Zhou and Wang 2013). Authors further concluded that a post should be as long as possible when a cast D&C is used, whereas the biomechanical performance of a fiber post was less sensitive to post length.

11.3.3 Practitioner's Clinical Expertise in Root Canal Preparation

(a) If canal preparation is off centered, the cutting edge of the drill might induce a ledge in the axial wall of root dentin. A root dentin wall with the ledge can be thinner, and stress can be concentrated due to the shape of ledge, which may increase the chance for root fracture failure when a cast D&C is used.
(b) Short canal preparation might lead to a short cast post, which in turn may increase post debonding and the chance of root fracture.
(c) A wide root canal preparation may leave a thin root dentin wall, which may increase the chance for root fracture.
(d) A root canal preparation that is too long or an inadequate gutta-percha removal technique may compromise the 4–5 mm apical seal. As seen in Chap. 1, an insufficient apical seal may result in endodontic failure.

11.3.4 Cementation/Bonding Technique for Cast D&C and Crown

Inadequate bonding of cast D&C to the root dentin or using a mechanically weak luting cement can increase post debonding as well as the possibility of root fracture. Inadequate bonding of full-coverage crown to the cast D&C/tooth margin or using weak cement can increase crown dislodgement chances (Heintze 2010; Kainose et al. 2014).

11.4 Clinical Sequences to Fabricate Cast D&C and Subsequent Full-Coverage Restoration

Once a cast D&C is selected as a choice of treatment over the prefabricated fiber post and core build-up from careful clinical and radiographic examinations, the endodontically treated tooth is prepared for a final full-coverage restoration. Clinical sequence of cast D&C and crown treatment is presented in Fig. 11.2.

Unless an endodontist has already prepared the canal space, the crown preparation is performed first before root canal preparation for cast D&C is initiated (Fig. 11.3). After an ideal crown preparation, the ideal post length is determined using a radiograph. The ideal post length is the longest possible length with 4–5 mm apical gutta-percha seal remained, while post width should not be thicker than one third of the root diameter. Unless an endodontist made a perfect canal preparation, further gutta-percha is removed using either a heated endo plugger (#5–7, #9–11) or the System B (SybronEndo). If none of these are available, proper size Gates-Glidden bur and Peeso reamer is used to remove gutta-percha and prepare the canal space (Fig. 11.4). Before finalizing the canal preparation, mid-treatment radiograph should be taken to make sure that the canal preparation is centered and an adequate apical seal is maintained. Using an adequately sized Peeso reamer, canal preparation is carefully finalized. Ideally, no gutta-percha or ledges or severe undercuts should be present on the axial wall of the prepared canal space to achieve maximum bonding of cast D&C to root dentin wall and to reduce chances of root fracture upon severe loading.

<u>First appointment</u>
- Pre-treatment radiograph
- Crown preparation
- Canal preparation
- Mid-treatment radiograph
- Finalization of canal preparation

<u>Option#1</u>
- Direct cast D & C pattern fabrication using EZ post
- Fabrication and cementation of provisional crown with EZ post

<u>Option#2</u>
- Impression of prepared canal using endowel pins
- Fabrication and cementation of provisional crown with EZ post

<u>Second appointment</u>
- Cementation of cast D & C
- Refinement of crown preparation over the cemented cast D & C
- Final impression for crown fabrication
- Provisional crown fabrication and cementation

<u>Third appointment</u>
- Crown cementation

Fig. 11.2 Clinical sequence of cast D&C and crown treatment

Fig. 11.3 Prior to canal preparation, an ideal canal preparation is performed, if an endodontist has not prepared canal space already

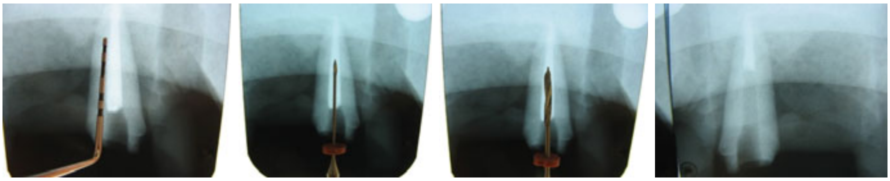

Fig. 11.4 The ideal post length is determined from the radiograph. Gutta-percha removal and canal preparation are performed using either a heated endo plugger (#5–7, #9–11)/System B or Gates-Glidden or Peeso reamer, if endodontist has not prepared the canal space already. Mid-treatment radiograph is strongly recommended prior to finalizing the canal preparation

11.4.1 Direct Pattern Technique Using EZ Post and Self-Curing Resin

Making a pattern directly from patient's mouth is indicated for an endodontically treated single root single tooth cast D&C restoration. The ideal shape of a direct pattern can be finalized in the patient's mouth, and a direct pattern will be sent to commercial laboratory for casting. This same technique can be used for fabrication of provisional restorations for both direct pattern and indirect impression cast D&C fabrication techniques. The post component of the cast D&C direct pattern is fabricated using EZ post system (white compound and plastic endowel; Merritt EZ Cast Post Inc.) (Leong et al. 2009). The white thermoplastic compound is heated until it becomes clear color melted state. The plasticized compound is picked up with the plastic endowel and placed into the prepared canal of a tooth in the patient's mouth. Once the material cools down to a white solid compound, the plastic endowel with the white compound is removed from the root canal (Fig. 11.5). If the removed white compound post has a void or is short from the orifice of the canal, additional melted compound is added, and post is placed back into the canal space to make a perfect post shape. Once the post portion of the cast D&C direct pattern is completed, the core portion of the direct pattern is fabricated using self-curing acrylic resin (Pattern Resin LS, GC America Inc.).

Once the endowel post is fully seated into the canal in patient's mouth, the polymer and monomer of the pattern resin is applied around the plastic endowel

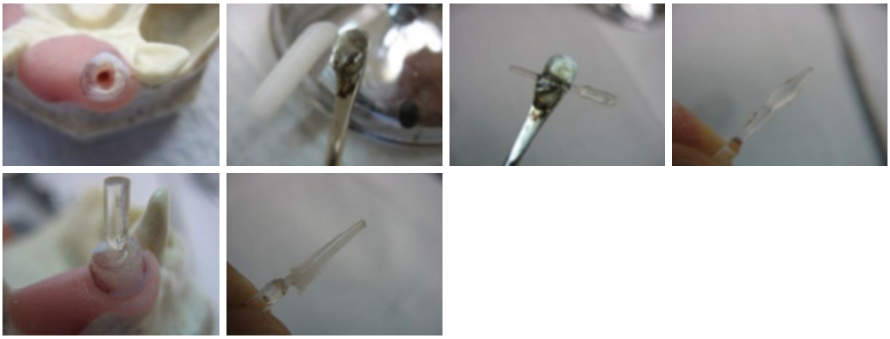

Fig. 11.5 Direct cast D&C pattern fabrication using the EZ post system (white thermoplastic compound and plastic endowel). The white compound material will turn into clear color once it is heated. Melted compound is picked up with plastic endowel and placed into the prepared canal. Once the color changes to white upon hardening, the plastic endowel with white compound is removed from the root canal

using a sable brush. One must be careful not to drop monomer or polymer of resin into patient's soft tissue. Once enough self-curing resin is applied around the endowel post and once resin is set, the core portion of the direct pattern is prepared using a diamond bur in situ. In case the direct D&C pattern is not stable during preparation, hold the pattern down in position using a periodontal probe. The core portion of direct pattern should be continuous from the remaining cervical portion of tooth structure, and no extra flash should be left. Remove completed one-piece direct D&C pattern to make sure that the core portion is well attached to the post section. If a vacuum shell preparation guide is available, try it over the core portion of the pattern to make sure that an ideal core shape is achieved. Once the core portion fabrication is completed to an ideal anatomy, a direct pattern of D&C is evaluated for its passive seating into the canal space. To reduce the chance of root fracture induced by cast D&C in the long term, the final cast D&C should seat passively without any friction to the axial wall of root dentin. Any white compound or red self-curing acrylic resin of direct D&C pattern engaging undercuts should be reduced using hot wax spatula and/or diamond bur until an absolute passive fit of direct pattern to the canal space is achieved (Fig. 11.6).

Set aside a direct pattern of D&C in a zipper bag to avoid misplacing it. One extra EZ post is created using the same technique to fabricate a one-piece provisional crown with EZ post. Once the post portion is fabricated, the handle of plastic endowel is turned into the nail head using a hot #7 wax spatula. Make sure that the white compound post with plastic nail head is seated fully in patient's mouth and the putty matrix for the provisional crown is not interfering with the nail head. The provisional restoration material is applied into the putty matrix, and this matrix is seated onto the tooth. After setting, the one-piece provisional crown with EZ post is removed from the canal space. At this point, we should inspect the provisional crown to make sure that the junction between the provisional crown and the white

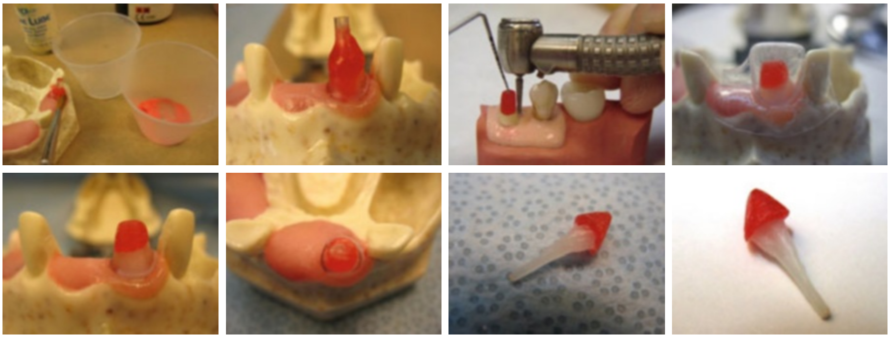

Fig. 11.6 The core portion of the cast D&C pattern is added around the plastic endowel using self-curing acrylic resin (Pattern resin) and a sable brush in patient's mouth. After setting, the core portion is prepared for an ideal abutment, while the direct cast D&C pattern is held down in position with a periodontal probe. A vacuum shell preparation guide can be used to confirm the ideal preparation of the core portion. Direct cast D&C pattern should have seamless transition to the remaining tooth structure and seat to the canal passively after eliminating any undercut engagement from the EZ post pattern

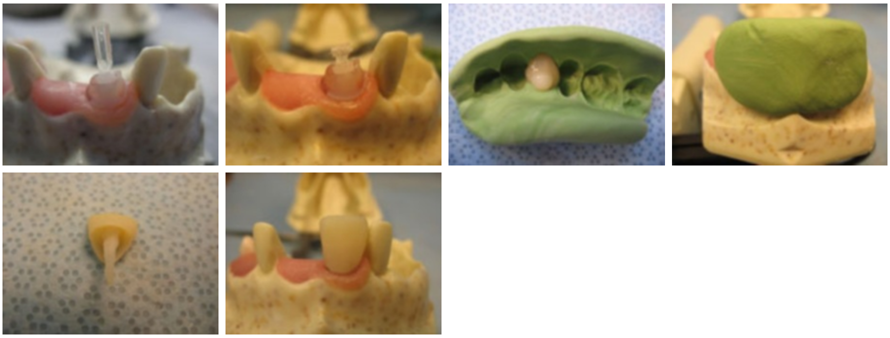

Fig. 11.7 An additional EZ post pattern is fabricated for fabrication of a provisional crown using same technique. Instead of adding the GC pattern resin to create the core portion of the direct pattern, a nail head is created using hot #7 wax spatula against plastic endowel. Provisional restoration material is applied into the putty matrix, and this matrix is seated onto the tooth. After setting, the one-piece provisional crown-EZ post is removed from the canal space. In this case, an undercut engagement of the EZ post is left for additional retention of provisional crown. The provisional crown-EZ post is cemented using a temporary cement

compound post section is strong and seamless. In this specific case, an EZ post undercut engagement is desirable to gain additional retention for the provisional crown. This crown is cemented using a temporary cement. The cement is applied only under the crown margin, not around the EZ post, to ease the removal of cement from the canal space at a subsequent appointment (Fig. 11.7). Occlusion should be carefully adjusted and patient is dismissed. The direct D&C pattern is then sent to commercial laboratory for casting.

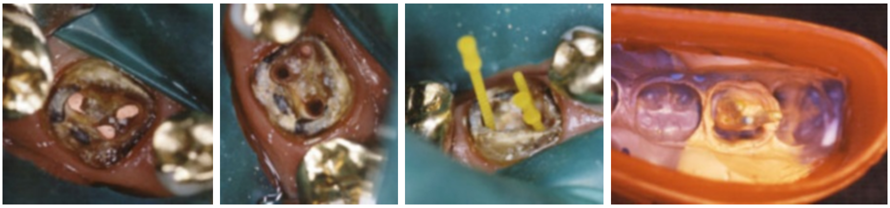

Fig. 11.8 Indirect impression technique

11.4.2 Indirect Impression Technique

This impression technique of the prepared canal space is indicated for multiple teeth cast D&Cs or multiple pieces of cast D&C in a multi-rooted single molar. Making direct D&C patterns for multiple teeth in the patient's mouth is not an efficient use of time. Also, if patient is pregnant or is allergic to self-curing acrylic resin, the indirect impression technique is indicated even for a single cast D&C fabrication.

Once both crown preparation and canal preparation are completed on multiple teeth or a multi-rooted tooth, plastic endowels of different sizes are tried into the canal spaces. The endowel should be fitting loosely without tugging into the canal, and it is cut to the proper length. Using a hot #7 wax spatula, a nail head is created as an additional retention during the impression procedure. The nail head location should be within the ideal core contour so that impression tray is not interfering with the plastic endowels. Each canal should have one plastic endowel with right size and length. All endowels are coated with polyvinyl siloxane (PVS) impression adhesive. Proper size gingival retraction cord is packed around the prepared tooth margin, and canals are cleaned and dried with paper points. A narrow syringe tip of PVS light body impression material is placed deep into the canal space, and the PVS impression material is expressed as syringe tip is withdrawn. Once the canal is filled with PVS impression material, an adhesive-coated plastic endowel is pushed into the canal through the PVS material. Further PVS impression material is applied around the tooth margin, and tray with monophase PVS impression material is seated into the patient's mouth. Once the impression material is set, the tray is removed, and the impression of the canal space and crown margin is carefully evaluated (Fig. 11.8). Remove gingival retraction cord around the tooth margin.

Using same EZ post technique, provisional restorations are fabricated and cemented with temporary cement. If desired, multiple provisional restorations are splinted for practitioner's convenience and better retention. Occlusion is carefully adjusted and patient is dismissed. Final PVS impression is sent to commercial laboratory for cast D&C fabrication. Two-piece key and keyway cast D&C fabrication laboratory procedure is presented in Fig. 11.9. Multiple cast D&C on multiple teeth using indirect impression technique is presented in Fig. 11.10. Once cast D&C is ready for cementation, self-adhesive dual-cured resin cement can be used to bond cast D&C against root dentinal wall. After 6–10 min of setting time, final crown preparation over the bonded cast D&C and tooth margin can be performed. Final

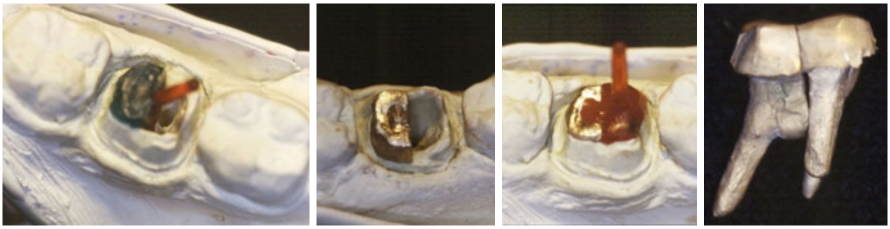

Fig. 11.9 Two-piece cast D&C laboratory procedures using stone cast fabricated from indirect impression technique

Fig. 11.10 Multiple cast D&C treatment sequence using indirect impression technique is presented (Courtesy of Dr. John Keyes)

PVS impression for a full-coverage crown fabrication is made. Provisional crown is fabricated and cemented with temporary cement. Once crown is ready for cementation, self-adhesive dual-cured resin cement can be used to bond full-coverage crown against cast D&C and tooth margin. Occlusion is carefully adjusted.

11.5 Cementation/Bonding of Cast D&C as well as Full-Coverage Restoration

Debonding of the cast D&C and dislodgement of crown are common causes of endodontically treated tooth restoration failure (Creugers et al. 2005). Choosing a right cementation/bonding material for cast D&C is a very important step to reduce chance of debonding and root fracture. Sandblasting of cast D&C with 50 μm alumina particles has been shown to increase retention of cast D&C when luted with resin cement (Rosenstiel et al. 1977). Roughening the root dentinal walls using a handheld diamond rotary cutting instrument (196D.644.090; Erlangen Post System; Brasseler) by rotating the instrument three times within the canal and the use of resin luting cements provided statistically significant increases in dowel retention (Nergiz et al. 2002). An in vitro study on the effects of different cements used with cast D&C found that the fracture resistance provided by a dual-cured resin cement (838 N) was significantly higher than that of resin-modified glass ionomer cement (613 N) and that of a zinc phosphate cement (643 N) (Young et al. 1985).

Two recent finite element analysis studies agreed that higher stress concentrated at the apex of cast D&C and cast post-dentin wall interface while the stress was concentrated at the cervical bonding area in fiber post and composite build-up case

(Balbosh et al. 2005; Santos-Filho et al. 2014). Authors further concluded that the bond of the cast post is essential for the survival of cast D&C restored tooth. Therefore, it is very important to have an absolutely passive fitting of the longest possible cast D&C against root dentin, and the sandblasted cast D&C should be bonded using self-adhesive dual-cured composite resin cement to the roughened root dentin. When cast D&C was bonded with self-adhesive resin cement, the fracture resistance was higher than that of the fiber post group (Zhou and Wang 2013; Santos-Filho et al. 2014). These results are in agreement with the meta-analysis study which concluded that cast posts had higher fracture resistance than fiber post based on 13 in vitro studies combined (Ellner et al. 2003).

A RCT compared clinical outcomes of different elastic moduli titanium and fiber posts bonded with self-adhesive resin cement on 91 patients over a 3-year period (Naumann et al. 2007). The results showed that both posts had no failures over the 3-year period. Titanium's elastic modulus is about 110 GPa which is higher than the one of gold, and this clinical results indirectly support the use of self-adhesive resin cement when gold alloy cast D&C is used.

A finite element study found that a sound tooth structure tended to transfer the load through the enamel, around the tooth center, and into the root dentin, indicating that the stress will be more concentrated on the structure with a higher elastic modulus and eventually transferred to the adjacent structure (Santos-Filho et al. 2014). This explains why stress from the loaded crown is more concentrated over the cast D&C with higher elastic modulus compared to fiber post and composite core build-up. To reduce the stress concentration on cast D&C and transfer of load into the root dentin, enough of die spacer upon crown fabrication against the cast D&C stone model may be necessary to provide an enough cement space when a composite resin cement is used between strong crown and cast D&C. Meanwhile crown margin should have an intimate contact against tooth margin, which can be either enamel or root dentin. With this intimate adaptation, more stress transfer from crown will occur to the tooth margin rather than to the cast D&C and then to root dentin wall. To make crown and cast D&C connection strong and retentive and induce better stress distribution, a dual-cured composite resin cement, such as self-adhesive resin cement, is recommended. The same self-adhesive resin cement can be used to bond cast D&C against root dentin walls as well as to bond crown against cast D&C/tooth margin.

An in vitro study showed that metal crown against ceramic crown, cast D&C against fiber post, 2 mm ferrule against 1 mm or 0 mm ferrule had significantly high fracture resistance (Santos-Filho et al. 2014). Authors postulated that alumina reinforced ceramic crown with higher elastic modulus increased the stiffness of the system therefore influenced stress distribution, regardless of cast post or fiber post used. The fracture resistance for cast D&C system ranged from 724 to 1026 N (Santos-Filho et al. 2014), which is higher than the maximum clenching force human can generate between maxillary and mandibular first molar teeth. If a patient has a bruxing or clenching parafunction, occlusal adjustment should be made carefully on cast D&C restored posterior teeth to increase the long-term success of the restoration.

11.6 Summary

Because studies show that keeping sound tooth structure as much as possible is the most important factor for the long-term success of the endodontically treated tooth restoration, it is discouraged to remove sound tooth structure just to eliminate undercuts so that cast D&C can be fabricated. Therefore, cast D&C should be considered only when there is one wall or less with/without ideal ferrule so that the cast D&C can be fabricated without unnecessary tooth structure reduction from the pulp chamber and/or internal axial walls of clinical crown.

As shown in many clinical studies, long-term restoration success rates of limited tooth structure of one wall or fewer with/without ferrule are not high, no matter which type of post is used (fiber post or cast D&C). Therefore, clinicians should approach cast D&C therapy as a final attempt to restore the compromised endodontically treated tooth. If cast D&C fails, extraction and implant or fixed partial denture restoration option should be considered to replace the failed tooth. Since cast D&C restoration will be the last resource to save the compromised tooth, the entire procedure should aim at creating the strongest connections between root-cement-cast D&C-cement-crown so that the restored tooth can last longest until it fails, without worrying about the failure mode of the restored tooth.

Prefabricated fiber post tends to fail mechanically, including post debonding, post and core fracture, and crown dislodgement when compromised tooth structure is present in an endodontically treated tooth. Cast D&C can eliminate at least one weak junction between fiber post and core build-up so that post and core fracture or crown dislodgement rates can be reduced. On the other hand, cast D&C tends to fail with root fracture mainly due to the presence of short post and the dissimilarity of elastic modulus of root dentin and cast D&C. Short or long post length did not affect root fracture rate significantly when fiber post was used but affected significantly when cast D&C was used. A short cast post was more related to a root fracture. Therefore, clinicians' expertise in canal preparation to achieve optimum post length and maintain maximum root dentin without sharp ledges created on axial walls of root dentin is very important to reduce root fracture failure rates, especially when dissimilar elastic modulus cast D&C are used.

With ideal canal preparation for post space while keeping most tooth structure available, an absolutely passive sandblasted cast D&C is recommended to be cemented with self-adhesive dual-cured resin cement to provide maximum retention as well as strength. When post is as long as possible while maintaining 4–5 mm apical seal and composite resin cement is sealing any gap between passive cast post and root dentin, the system of cast D&C-resin cement-root can be a strong structure, making 0.2 mm thick periodontal ligament and surrounding bone bear most of occlusal loads. Cast D&C does not have a weak junction, which is present between prefabricated fiber post and core build-up. Therefore, the deformation of cast D&C junction as well as cast core itself might be smaller than the deformation of fiber post and core build-up system. A combined technique of using passively fitting one-piece cast D&C with long post length and bonding cast D&C with composite resin cement in endodontically treated tooth with limited tooth structure may reduce the rates of typical cast D&C failures, root fracture, debonding of cast D&C, and dislodgement of crown.

Absolutely passive full-coverage crown against a cast D&C portion of a tooth can be further cemented with self-adhesive dual-cured resin cement to provide maximum retention of the crown as well as strength of the system, crown-resin cement-cast core/tooth margin. By achieving the strongest and most retentive solid system of root-resin cement-cast D&C-resin cement-crown, a cast D&C restored endodontically treated tooth may work similarly to virgin tooth while periodontal ligament works as a shock absorbing mechanism, thus improving long-term success and reducing the root fracture incidence.

Even though there are conflicting studies regarding the validity and advantages of cast D&C over the prefabricated fiber post and core build-up system, careful planning and skillful execution of cast D&C therapy of making the system the strongest possible using ideal cast D&C and resin cements may be a preferred choice over the prefabricated fiber post and core build-up in an endodontically treated tooth with limited tooth structure. Cast D&C might benefit patients who want to save their compromised teeth as long as possible as a last resort and are willing to accept the extraction and dental implant or fixed partial denture therapy upon cast D&C's failure.

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Clinical Sequence

12

George Gomes and Jorge Perdigão

Abstract

This chapter illustrates the step-by-step treatment of two maxillary central incisors restored with fiber posts luted with a self-adhesive cement, followed by composite resin buildups and porcelain-fused-to-zirconia crowns. Two videos will also demonstrate the use of materials and instruments necessary to lute fiber posts in the root canal with adhesive techniques.

Below is the step-by-step protocol for luting fiber posts using a self-adhesive cementation technique or a conventional cementation technique.

12.1 Self-Adhesive Cementation Technique

Materials

I. Fiber post
II. Self-adhesive resin cement
III. Dual-cured composite core buildup

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1. Rinse canal with (distilled) water and dry with paper points.
2. Insert the elongation tip into the canal and inject the self-adhesive cement starting at the apical area.
3. Immediately insert the post into the canal keeping a gentle vertical pressure on the post for 5–10 s.
4. Remove excess cement around the post with microbrush; light-cure for 40 s.
5. Refresh the dentin substrate with a slow-speed round bur in case the excess of self-adhesive resin cement extended to the coronal dentin. Etch exposed dentin and enamel with 30–40 % phosphoric acid for 15 s, rinse for 10 s, and gently air-dry.
6. Apply the dentin adhesive actively for 20 s, and gently air-dry to evaporate solvent; light-cure for 20 s in case it is recommended by the respective manufacturer.
7. Depending on the size of the preparation, the composite core buildup material may be applied freehand or with a matrix band. In case a clear celluloid crown form is needed to shape the core buildup, select the corresponding size. Trim the celluloid crown form with scissors to adjust the matrix to the tooth structure.
8. Inject the composite buildup; light-cure for 40 s from different directions.

12.2 Conventional Cementation Technique

Materials

I. Fiber post
II. Adhesive system
III. Dual-cured composite resin cement
IV. Dual-cured composite core buildup

1. In case the etch-and-rinse technique is preferred, acid-etch root canal walls and coronal aspect of preparation with 30–40 % phosphoric acid for 15 s. If needed, use paper points to reach all canal walls.
2. Rinse for 10 s; dry canal with paper points.
3. Apply the dentin adhesive into the root canal with a small-tip microbrush, and rotate the brush several times inside the canal; apply the adhesive to the coronal aspect of the tooth actively for 20 s.
4. Remove adhesive solvent from the canal with paper points until a paper point returns dry from the canal. Gently air-dry the adhesive in the coronal aspect to evaporate the solvent. Light-cure for 20 s if recommended by the respective manufacturer.
5. Brush residual adhesive on the post surface, air-dry for 5 s, and light-cure for 10 s.
6. Insert the dual-cure resin cement into the canal starting at the apical area.
7. Immediately insert post into the canal; keep a light vertical pressure for 5–10 s.
8. Light-cure the composite material for 40 s.
9. Depending on the size of the preparation, the composite may be applied free-hand or with a matrix band. In case a clear celluloid crown form is needed to shape the core buildup, select the corresponding size. Trim the celluloid crown form with scissors to adjust the matrix to the tooth structure.
10. Inject the composite buildup, and light-cure for 40 s from different directions.

Clinical Case Sequence of Two Restorations with Fiber Posts, Composite Buildups, and Porcelain-Fused-to-Zirconia Crowns

Fig. 12.1 The major complaint of this 24-year-old female patient was her compromised esthetics – "I avoid smiling all the time." There was a history of trauma to maxillary central incisors, which had been endodontically treated and restored with porcelain-fused-to-metal crowns. Patient's medical history was noncontributory

Figs. 12.2, 12.3, and 12.4 Baseline views of the esthetically compromised crowns

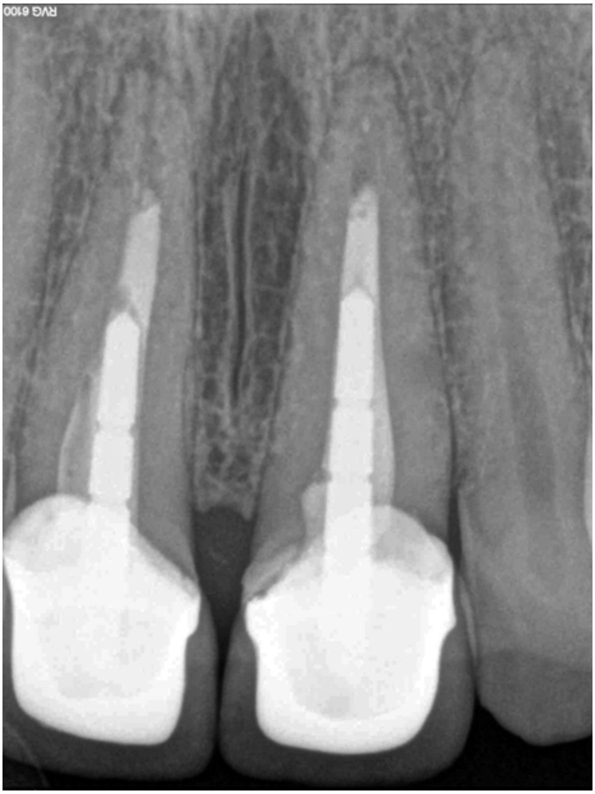


Fig. 12.5 Maxillary central incisors – periapical radiograph of the baseline condition showing enlarged root canals with prefabricated metal posts and deficient root canal treatment

Fig. 12.6 After a waxed-up model was shown to the patient, she approved the treatment plan. The existing porcelain-fused-to-metal crowns and respective luting cement were removed

Fig. 12.7 Prefabricated metal posts were removed with an ultrasonic device and a small diamond bur in high-speed handpiece

Fig. 12.8 The prefabricated metal post is being removed from the root canal

Fig. 12.9 Custom-fabricated provisional restorations were made with a bis-acryl composite resin (Protemp Plus/4, 3M ESPE)

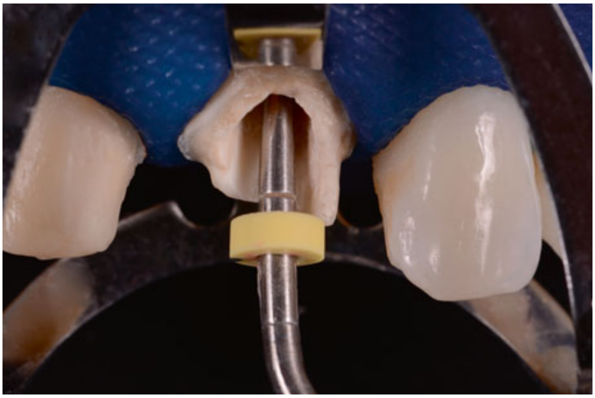


Fig. 12.10 After the root canals were retreated, gutta-percha was removed with the System B Heat Source (SybronEndo) to the root canal length previously determined in the periapical radiograph. Residual gutta-percha was then hand-condensed to leave an adequate apical seal of at least 5 mm

Fig. 12.11 Periapical radiograph after endodontic retreatment

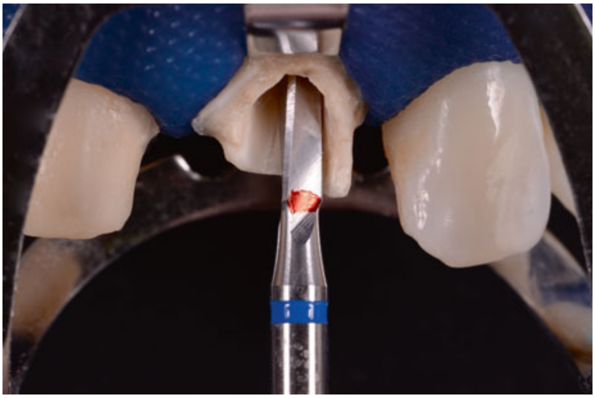


Fig. 12.12 As the root canal had been widened for the preexisting metal post, a wide fiber post was selected without the need to remove more dentin from the root canal walls. The respective drill was used just to refresh the root dentin walls and create a new smear layer

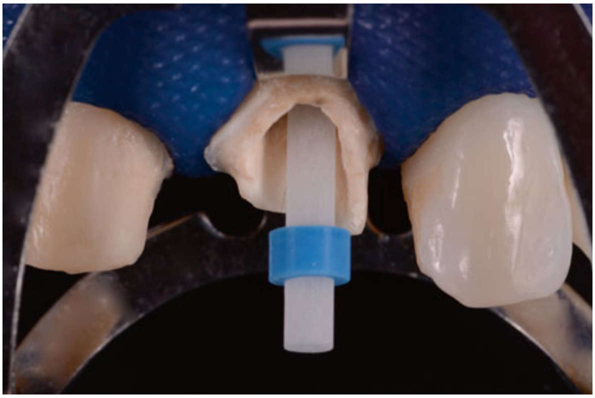


Fig. 12.13 The respective double-tapered fiber post was tried in (#3 RelyX Fiber Post, 3M ESPE) and a radiograph taken to check the adaptation to the root canal

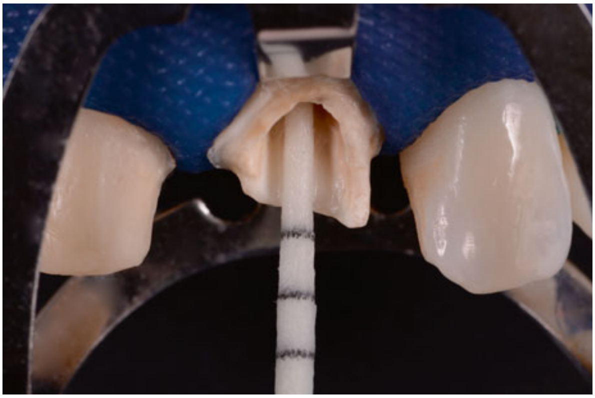


Fig. 12.14 The root canal was rinsed with 2.5 % NaOCl and dried with paper points. Next, the canal was rinsed with 95 % ethanol with a Monoject (Covidien) irrigation syringe and dried with paper points

Fig. 12.15 Thee self-adhesive cement RelyX Unicem 2 (3M ESPE) was injected into the canal with an elongation tip, starting at the apical aspect of the post space

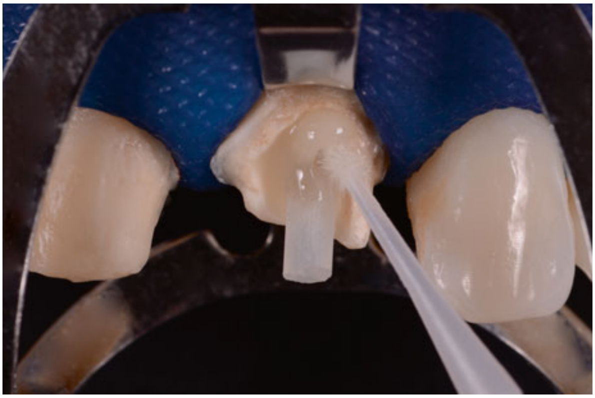


Fig. 12.16 Excess cement was removed with a disposable brush to avoid blocking the area around the post, which serves as a retentive cove for the composite build up material

Fig. 12.17 The exposed self-adhesive cement was light-cured for 40 s

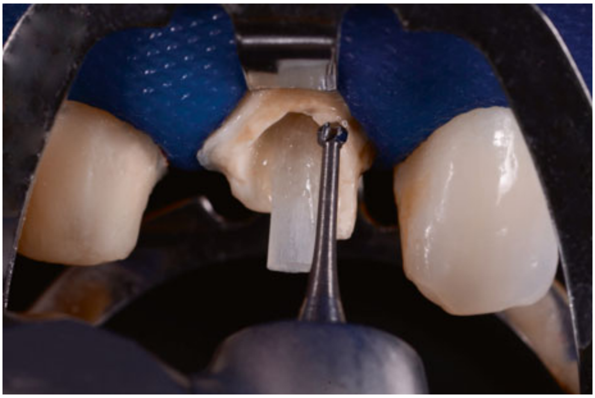
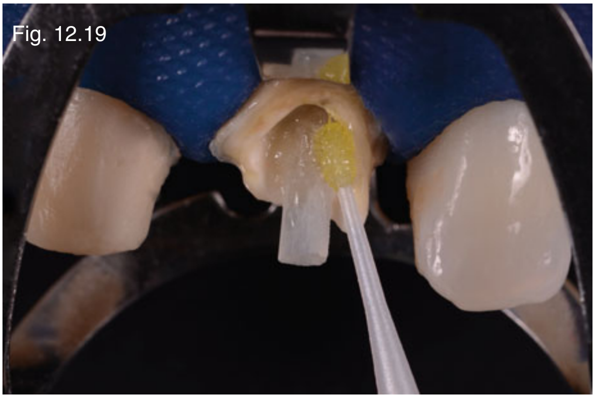
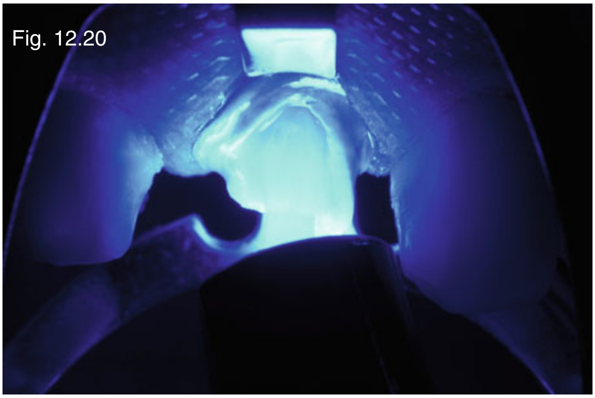


Fig. 12.18 The dentin surface was refreshed with a slow-speed round bur to remove residual cement debris and create a new smear layer





Figs. 12.19 and 12.20 After etching with 34 % phosphoric acid for 15 s and rinsing for 10 s followed by gently air-drying, a dentin adhesive was applied, gently air-dried to evaporate the solvent, and light-cured for 20 s

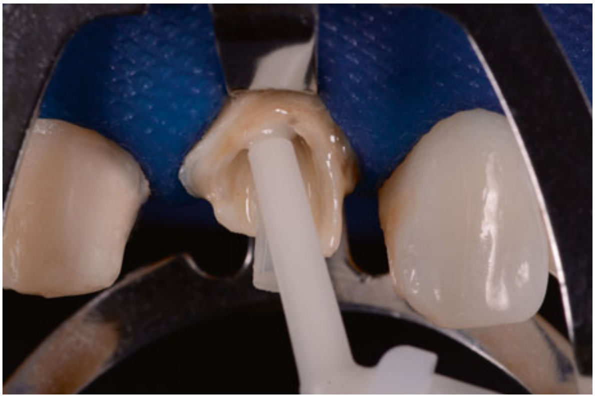


Fig. 12.21 A dual-cure composite buildup material (Paracore, Coltene) was injected and light-cured for 40 s from the buccal and 40 s from the lingual aspects

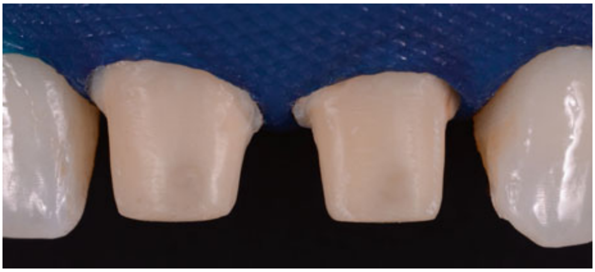
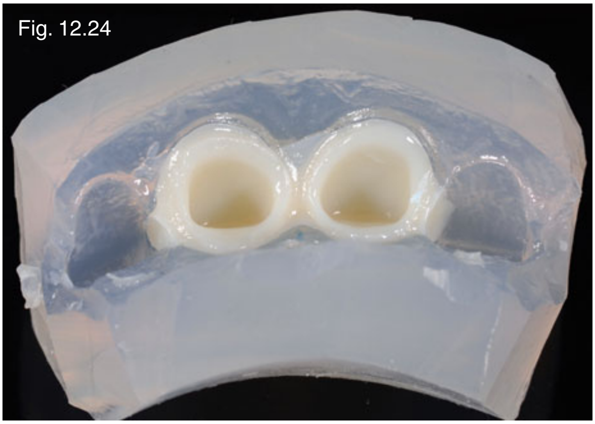


Fig. 12.22 The preparations were finished after 15 min

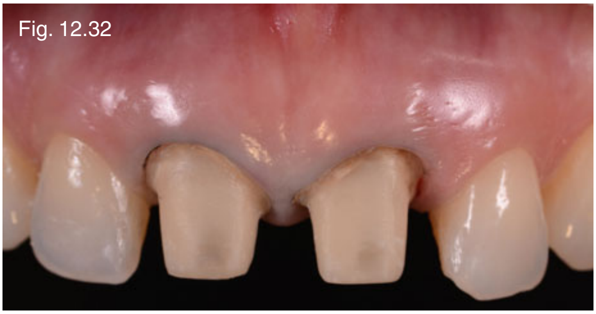
Fig. 12.23 Periapical radiograph showing the post cemented in the root canal and core buildup

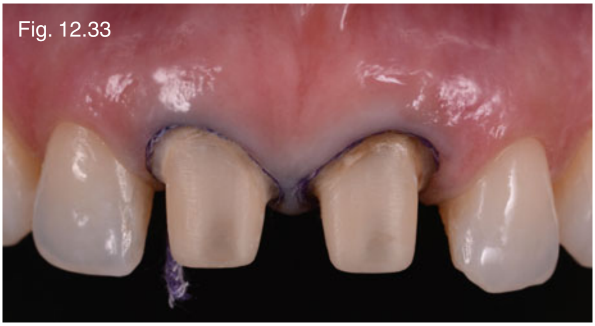


Figs. 12.24, 12.25, and 12.26 New custom-made provisional restorations were fabricated using a polyvinyl siloxane matrix filled with bis-acryl composite resin (Protemp Plus/4, 3M ESPE). The polyvinyl siloxane template reproduced the preoperative wax-up to serve as a blueprint for the definitive restorations. Adjustments were made as per the patient's suggestions. The provisional restorations were polished with sandpaper disks and rubber polishing points

Figs. 12.27, 12.28, and 12.29 The natural look of the provisional restorations served as blueprint for testing out the changes in esthetics, contour, and occlusion, before the definitive restoration were made

Fig. 12.30 Shade of the preparations was registered and a shade map was drafted





Figs. 12.31, 12.32, and 12.33 A double retraction cord was packed

Figs. 12.34 and 12.35 Impression was taken using Imprint 4 Penta Heavy and Imprint 4 Light Regular Set (3M ESPE)


Fig. 12.34

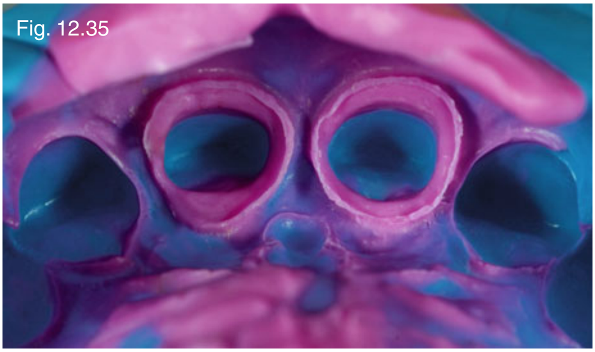
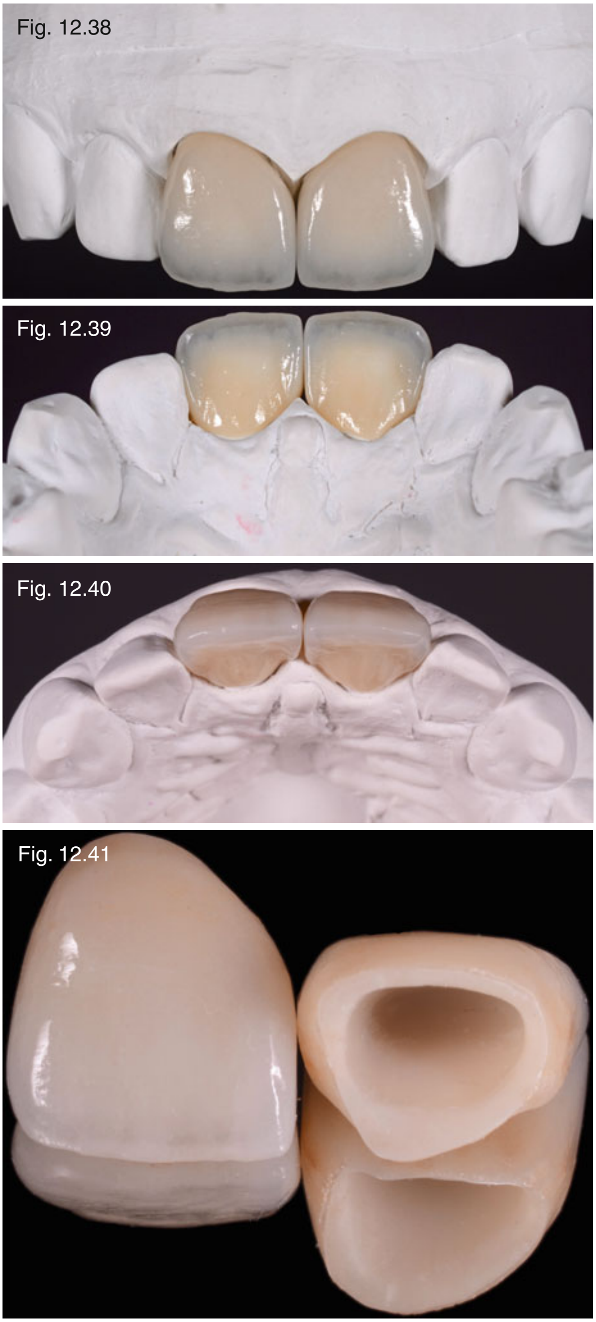


Fig. 12.35

Figs. 12.36 and 12.37 The provisional restorations were adjusted and recemented


Fig. 12.36

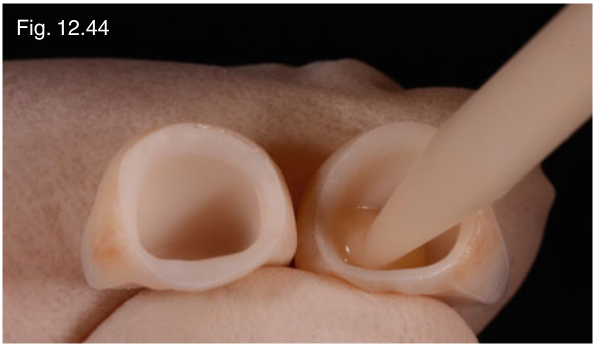

Fig. 12.37



Figs. 12.38, 12.39, 12.40, and 12.41 Definitive restorations – zirconia copings (Lava Plus High-Translucency, 3M ESPE) veneered with IPS e.max Ceram (Ivoclar Vivadent). These two materials have similar coefficients of thermal expansion

Fig. 12.42 Try in with water to check the marginal fit

Fig. 12.43 After the restorations were deemed clinically acceptable, the intaglio surface was sandblasted with aluminum oxide particles (≤50 μm, 2 bars)



Figs. 12.44 and 12.45 A self-adhesive resin cement (RelyX Unicem 2, 3M ESPE) was used to lute the restorations

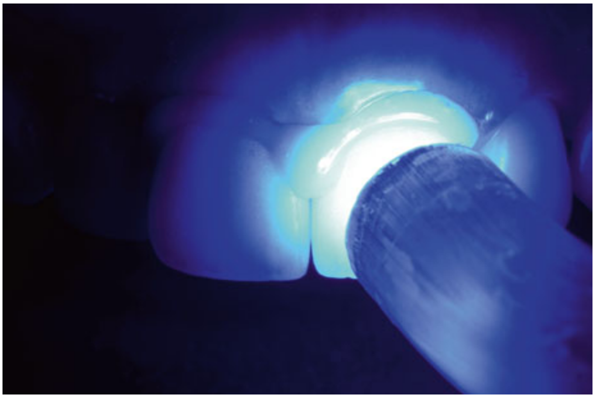


Fig. 12.46 The cement was tack-cured for 2 s

Fig. 12.47 The excess material was peeled off in one piece

Fig. 12.48 The retraction cords were removed

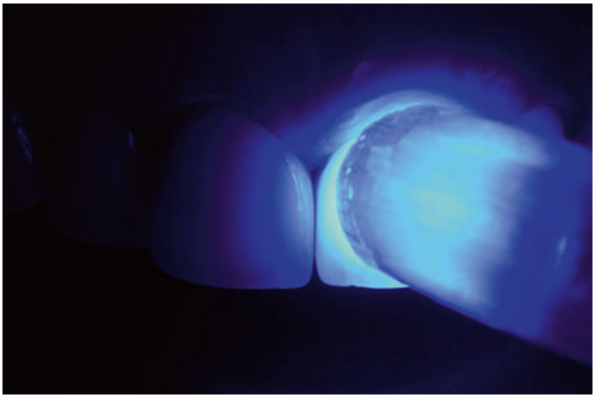


Fig. 12.49 The margins were irradiated with an LED light-curing unit to increase the degree of conversion of the resin cement in contact with the oral fluids immediately after the cementation procedure

Fig. 12.50 Patient was extremely satisfied with the esthetic and functional outcomes