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The Post–endodontic Adhesive Interface: Theoretical Perspectives and Potential Flaws

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Abstract

Introduction

The aim of this review was to analyze the potential of successful bonds of endodontic posts to radicular dentin as well as the limitations of the post–endodontic adhesive interface.

Methods

The MEDLINE/PubMed and Web of Science electronic databases were searched. The search was augmented by a manual search of the pertinent bibliographies.

Results

The post–endodontic adhesive interface finds application in the endodontic cohesive units. Many techniques and materials exist to improve the bond between endodontic posts and resin-based materials as well as between resin-based materials and radicular dentin. Different techniques used for the adhesion of metallic and fiber-reinforced posts are discussed and critically analyzed.

Conclusions

Although adhesive cementation of endodontic posts is popular, a long-term predictable bond may be compromised because of procedures related to the endodontic treatment and/or the adhesive cementation procedures. Microleakage and degradation phenomena may further jeopardize the post–endodontic adhesive interface.

Key Words
Adhesion; endodontic dowel; endodontic post; radicular dentin; resin cement

Significance

> Although adhesive cementation of endodontic posts is popular, long-term predictable bonds may be compromised because of procedures related to the endodontic treatment and/or the adhesive cementation procedures. Microleakage and degradation phenomena may further jeopardize the post–endodontic adhesive interface.

Adhesive cementation of intraradicular posts has become a popular treatment modality. Traditionally, the purpose of the cement is to fill the gaps between the prepared post space and the post. The main retentive value of the post is provided by the geometric characteristics of the post and the properties of the cement [1, 2]. However, the development of resin cements significantly expanded the role cements play. Resin cements exhibit a higher number of cycles to preliminary failure [(3)] and better retention [4, 5, 6, 7], even if the post has a reduced length [8], 9. They also appear to be the most suitable for the cementation of fiber posts [6, 10, 11]. Finally, there is some evidence that the use of resin cements may increase the fracture resistance of teeth restored with a cast post and core [(12)].

The post–endodontic adhesive interface is 1 of the interfaces that form the cohesive endodontic units or “monoblocks.” The “cohesive endodontic unit” model is based on the idea that a strong bond could be achieved among radicular dentin, post, and foundation core material [(13)]. Also, the different materials would have similar flexural properties [(13)]. As a result, they function cohesively and not as a mechanically heterogeneous unit [(14)]. The term "monoblock" is a misnomer because it refers to structures made from 1-piece materials, and as such it cannot describe a multi-interface adhesive system accurately. Monoblocks have been further classified into primary, secondary, and tertiary based on the number of the different existing interfaces [(13)]. This model was first described with the adhesive cementation of fiber posts using resin cements and the bonding of foundation core composite resin materials to the post and the remaining dentin. However, adhesive cementation could also be achieved today using metallic posts [(15)]. This review aims to discuss the potential of achieving a predictable bond between different post materials and dental substrates as well as the possible limitations that may lead to failure of the post–endodontic adhesive interface.

Literature Search Strategy

An online search of the literature was conducted using the MEDLINE/PubMed and Web of Science databases. The key words used to search the electronic databases were combinations of the following: "endodontic post" OR "endodontic dowel," "adhesion" OR "bonding," "resin cement" OR "composite resin," "dentin," "metals" OR "alloys," "surface treatment," and "monoblock." The search results were limited to articles published in English since 1980. Additionally, the following journals were manually searched to identify relevant articles: *Journal of Endodontics*, Journal of *Prosthetic Dentistry*, and Journal of *Prosthodontics*. Inclusion criteria for full-text review were that the selected articles should investigate or discuss the bonding of composite resin–based products to various types of endodontic post materials and dentin.

Results

After duplicate articles were removed, titles and abstracts were reviewed to select relevant articles. Because of the nature of the search, a variety of article types were included, such as systematic reviews, narrative reviews, and *in vitro* studies. No clinical studies were identified. A total of 66 articles were identified that were related to the aim of this review. Articles that provided additional relevant information but were not related to bonding of endodontic posts to radicular dentin were also included to provide a more complete review of the materials and techniques described, bringing the total number of articles to 118. The articles were subsequently organized into the following topics: bond to fiber-reinforced posts, bond to metallic posts, bonds to radicular dentin, and microleakage and degradation phenomena.

Discussion

Bond to Fiber-reinforced Posts

Fiber-reinforced posts consist of fibers (glass, carbon, quartz, or polyethylene) embedded in a polymer–epoxy resin matrix. The purpose of the fibers is to increase the tensile and fatigue strength of the post and to enhance its volumetric stability. The epoxy matrix is highly cross-linked, with a very high degree of polymerization conversion. Its purpose is to support and protect the fibers [(16)]. The most common technical complication of endodontically treated teeth restored with fiber posts is post debonding [17, 18]. Interpenetration between resins and the fiber post material is feasible in products with an intrapolymer network–polymer matrix (ie, everStick Post [GC America Inc, Alsip, IL]) [(19)]. This is consistent with the absence of adhesive failures of post systems with an intrapolymer network–polymer matrix [(20)]. The direction of the fibers can be longitudinal or vertical and is product dependent. Longitudinal fibers may allow for a better bond with the tooth, resin cement, and foundation core material [(21)]. However, when the fibers are vertically oriented, the post generally has superior mechanical properties, increased stiffness, fatigue, and fracture resistance [(22)]. The high degree of polymerization conversion of the resin matrix in fiber posts may result in a poor bond between resin cements and the post surface because of the lack of free functional groups [(23)]. Adhesion to the fiber post surface is significantly inferior to dental substrates [(24)].

Many techniques suggest modification or treatment of the post surface to increase the adhesion of resin cements. These techniques include, but are not limited to, the application of hydrofluoric acid [(25)], phosphoric acid [(26)], hydrogen peroxide [27, 28, 29, 30, 31], methylene chloride [(29)], potassium permanganate [(28)], silane [25, 27, 28, 29, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40], tribochemical coating systems [25, 39], and airborne-particle abrasion [26, 35, 36]. Surface conditioning of fiber posts with silane, tribochemical coating, phosphoric acid, hydrofluoric acid, or potassium permanganate is not always effective [25, 26, 29, 32, 34, 37, 40]. Silane could increase the bond strength, but a fiber post may have no free functional groups to react with silane [(41)]. However, silane could be effective when it follows other post pretreatment techniques [25, 42]. Hydrogen peroxide functions through dissolution of the epoxy resin matrix and appears to be more effective when compared with methylene chloride [(29)]. Hydrogen peroxide is also more effective when applied to glass fiber posts when compared with quartz fiber posts [(29)]. As far as air-particle abrasion is concerned, it could increase the retention of resin on the surface of fiber posts [(36)]. Air-particle abrasion causes partial removal of the epoxy resin matrix that exposes the fibers, increases the available surface area, and increases the surface roughness of the fiber posts [(35)]. Subsequently, resins could interact through micromechanical interlocking and slide friction [(36)]. Whether this method increases post retention and bonding is controversial [26, 35, 36]. Nevertheless, it is generally agreed that even though air-particle abrasion may increase bond strengths it may be an aggressive procedure that can alter the morphologic characteristics and the properties of the fiber posts [35, 36]. Therefore, its application cannot be safely recommended for all fiber post systems. Thus, all the techniques previously described are highly material dependent, and there is no sound scientific basis for their predictable universal application on all fiber-reinforced posts.

Bond to Metallic Posts

Metallic posts, prefabricated or custom, can be fabricated from high noble alloys or various types of base metal alloys (nickel-chromium alloys, stainless steel, and titanium). A resin-based material could bond to a metal oxide layer through hydrophilic bonds. However, this bond is relatively weak and prone to hydrolysis [(43)]. Techniques attempting to enhance the bond quality between metal surfaces and resin-based materials can be mainly divided into 2 categories: surface modification techniques and techniques involving the application of primers containing functional monomers.

Surface modification techniques include pyrochemical silica coating techniques [(44)], tribochemical coating systems [(45)], titanium dioxide coating systems [(43)], and spark erosion [(46)]. These techniques create a silicified oxide layer on the metal surface that could lead to a predictable bond with resin-based materials. The tinplate technique could also be added in this category, increasing the bond strength of composite resins to noble alloys through the electrochemical deposition of a layer of tin [(47)]. Generally, surface modification techniques could be used for both noble and base metal alloys [(47)]. Their main disadvantage is that they are more complicated procedures and require special equipment. Also, they cannot be easily applied chairside.

Functional monomers contain groups of atoms or bonds that are responsible for a specific chemical reaction. These functional monomers have a chemical affinity to metals and concurrently copolymerize with the structural monomers of resin-based materials. Primers containing functional monomers can be further divided into primers for base metal alloys/titanium, primers for noble alloys, and universal primers. Base metal alloy primers include functional monomers that contain phosphate or carboxylic acid functional groups [(48)]. Examples include 10-methacryloyloxydecyl dihydrogen phosphate and 4-methacryloyloxyethyl trimellitate anhydride, which create an ionic bond with resin-based products [(48)]. The application of 10-methacryloyloxydecyl dihydrogen phosphate results in a better bond than 4-methacryloyloxyethyl trimellitate anhydride when applied on nickel-chromium alloys [(49)]. It forms its most predictable bond with commercially pure titanium and titanium alloys [50, 51, 52, 53]. Noble metal alloy primers include functional monomers that contain thionic groups. An example is 6-(4-vinylbenzyl-n-propyl) amino 1,3,5-triazine-2,4-dithiol, dithione tautomer, which also creates an ionic bond [(54)]. Finally, the universal primers consist of a combination of monomers, 1 for base metal alloys and 1 for noble alloys [(55)]. Alternatively, they may consist of dual functional monomers, which contain both phosphate and thionic functional groups in a single molecule [(56)]. An example is thiophosphate methacryloyloxyalkyl. The main advantage of the universal primers is that only 1 primer is necessary and can be applied to any kind of alloy. Examples of the metal primer products currently available are listed in Table 1.

Table 1. Examples of Available Primers for Bonding Resin-based Materials to Metal Surfaces

Product	Functional monomers	Use	Manufacturer
ALLOY PRIMER	10-MDP/VBATDT	Universal	Kuraray America Inc, Houston, TX
Futurabond M+	Proprietary	Universal	VOCO America Inc, Indian Land, SC
GC METALPRIMER II	MEPS	Universal	GC America Inc, Alsip, IL
META FAST	4-META	Noble alloys	Sun Medical Co Ltd, Moriyama, Japan
METALTITE	MTU-6	Noble alloys	Tokuyama Dental America Inc, Encinitas, CA

Product	Functional monomers	Use	Manufacturer
M.L. Primer	10-MDDT/6-MHPA	Universal	Shofu Dental Corporation, San Marcos, CA
Monobond Plus	Methacrylated phosphoric acid ester/proprietary	Universal	Ivoclar Vivadent Inc, Amherst, NY
MTL-V Primer	Proprietary	Noble alloys	Parkell Inc, Edgewood, NY
V-PRIMER	VTD	Noble alloys	Sun Medical Co Ltd, Moriyama, Japan
Z-Prime Plus	10-MDP/proprietary	Universal	Bisco Inc, Schaumburg, IL

4-META, 4-methacryloyloxyethyl trimellitate anhydride; 10-MDDT, 10-methacryloyloxydecyl-6,6-dithiooctanate; MDP, 10-methacryloyloxydecyl dihydrogen phosphate; MEPS, thiophosphate methacryloyloxyalkyl; MTU-6, 6-methacryloyloxyhexyl 2-thiouracil-5-carboxylate; 6-MHPA, 6-methacryloyloxyhekyl phosphonoacetate; VBATDT, 5-(4-vinylbenzyl)-2-thiobarbituricacid (5VS), 6- (4-vinylbenzyl-n-propyl) amino-1,3,5-triazine-2,4-dithione; VTD, 6-(4-vinylbenzyl-n-propyl) amino 1,3,5-triazine-2,4-dithiol, dithione tautomer.

Air-particle abrasion with aluminum oxide (Al_2O_3) particles is necessary for the primers to be effective. The principal mechanism is not clear, but it may act through an increase of the surface area (micromechanical retention), a decrease of surface tension (adhesion and wettability), and/or oxidization of base metal alloys (chemical bond) [49, 56, 57]. However, air-particle abrasion may alter the character of the metal surface. Aluminum oxide particles may get trapped and partially cover the original alloy elements in the superficial layer [(58)]. The chemical affinity of aluminum particles to phosphate monomers may be responsible for the improved performance of some primers after air-particle abrasion [(49)].

Bond to Radicular Dentin

Bonding to dentin is considered a predictable clinical procedure. Traditionally, this could be achieved by etching the dentin and applying a primer and an adhesive. Etching can be achieved with phosphoric acid or self-etching primers (SEPs). Its purpose is to remove the smear layer and to demineralize the dentin to an extent of 2–10 μm [(59)]. Etchants cause partial removal of peritubular dentin and result in widening of the dentin tubules. Also, they demineralize the intertubular dentin and expose the collagen scaffold [(60)]. Two mechanisms contribute to the resin-to-dentin bond strength: resin tag penetration and resin penetration into the dentin tubules [(61)]. Resin tag penetration is the most important mechanism. It is achieved through the formation of the hybrid layer on the intertubular dentin by penetration, and later polymerization, of the hydrophilic and hydrophobic adhesive monomers into the exposed collagen network [(60)]. The presence of some amount of moisture is important during this process because it allows for better penetration of the adhesive monomers in the collagen network and dentin tubules after acid etch treatment [(62)]. The presence of a moderate amount of moisture results in superior push-out bond strength and lower nanoleakage [(63)]. The second mechanism, penetration into the dentin tubules, results in less retention. The tubules are covered by peritubular dentin, which is approximately 40% more mineralized than intertubular dentin and has less collagen fibers [(64)]. This results in less successful hybridization [(61)]. The use of 3-step adhesive systems (etching, primer, and adhesive) is still considered the gold standard for bonding to coronal dentin because they show less marginal defects after 1 year [(65)] and a better marginal seal after 3 years [(66)].

Bonded post systems require a successful bond to radicular dentin. Resin bonding to apical radicular dentin could be less strong compared with bonding to cervical radicular and coronal dentin [67, 68, 69, 70, 71]. Cervical radicular dentin is morphologically similar to deep coronal dentin [(64)], but apical radicular dentin presents important differences. In particular, the number and diameter of dentin tubules gradually decrease toward the root apex [(72)]. The tubule number decreases dramatically from approximately 42,360 per mm^2 to 8190 per mm^2 from the cervical to the apical radicular dentin [(73)]. This may result in decreased adhesive infiltration in the apical portion [(74)]. Phosphoric acid or SEPs did not change the dentin tubule density; however, the cross-sectional area of the tubules increased significantly after the use of SEPs and even more after the use of phosphoric acid [(64)]. Also, radicular dentin shows convex, dome-shaped irregular projections (calcospherites), which may affect the diffusion of adhesive monomers [64, 75]. According to a theoretic model, these differences could lead to a 90% reduced bond strength to radicular dentin [(72)]. However, it is unclear whether these morphologic differences could be important because some studies found higher bond strengths in the apical third of the post space preparation compared with the middle and cervical third [76, 77]. Other studies found no differences in the bond strength between coronal and radicular dentin [(78)] or between the different portions of radicular dentin [79, 80].

Procedures related to endodontic treatment, post space preparation, and post cementation may further impact the quality of the post–endodontic adhesive interface. Chemomechanical preparation materials containing peroxides and glycol (RC-Prep [Premier Dental, Plymouth Meeting, PA]) may decrease the bonding capability of resin cements to radicular dentin [(81)]. Residual peroxides may oxidize the dentin collagen network or may further break down into oxygen, inhibiting the polymerization of resin-based products [(81)]. Glycol lubricant may be difficult to remove and may inhibit proper monomer polymerization [(81)]. The use of eugenol-based sealers during endodontic treatment has well-known effects on the bonding to dentin and polymerization of composite resin materials [77, 79, 82, 83, 84, 85]. The effect of eugenol is also time dependent because it may continue to penetrate the dentin tubules over time [(86)]. During post space preparation, reamers are used to remove gutta-percha (GP), which results in a heat-plasticized smear layer rich in endodontic sealer and GP remnants [70, 87]. There are no scientific data to suggest that this type of smear layer can be successfully removed by etching. The absence of a chemical bond between the polyisoprene component of GP and the methacrylate component of resin cements may further jeopardize the bond to dentin [(88)]. Etchants may not flow completely in the root canal, causing inadequate exposure of the collagen fibers. Furthermore, etchants cannot be removed completely, and residual etchants may cause low pH-related inhibition of polymerization of resin-based materials [(89)]. The presence of excessive amounts of moisture is another challenge in the root canal environment (63, 71), and voids between posts and root canal walls are evident when resin cements are used [15, 90, 91, 92]. Incomplete light penetration in the post space can also result in incomplete polymerization of both the adhesive agent and the resin cement [93, 94].

Even if there was successful etching and monomer penetration into the radicular dentin, the geometric characteristics of the configuration of the root canal may not be favorable. The configuration factor (c-factor) was first described for coronal direct restorations using composite resin in 1987 [(95)]. The c-factor can vary from 0.5 to 5 and depends on the ratio of bonded to unbonded surfaces [(95)]. The root canal simulates a very deep class I cavity in which the c-factor value may exceed that of 200, resulting in uncontrolled resin polymerization contraction [(96)]. The resulting stress from volumetric shrinkage may exceed the bond strength with radicular dentin [70, 97].

There are ways to overcome some of the potential problems. Ascorbic acid or sodium ascorbate act as reducing agents and may reverse the negative oxidizing effects of sodium hypochlorite (NaOCl) or RC-Prep on certain adhesive systems [(81)]. The use of eugenol-based sealers has been limited in favor of resin-based sealers that do not inhibit the polymerization of composite resins [84, 85]. Also, preparation of radicular dentin with chlorhexidine solution or ethanol may improve the durability of the bond when a self-etching system is used [82, 98, 99]. Chlorhexidine may preserve the bond to radicular dentin even after cyclic loading and when a total etching system is used [100, 101]. Chlorhexidine inhibits degradation caused by dentin matrix metalloproteinases [(102)], and ethanol facilitates better penetration of hydrophobic monomers into dentin [(98)]. The use of EDTA and NaOCl may eliminate the radicular smear layer more efficiently, resulting in improved retentive strength when a self-adhesive resin cement is used [93, 99, 103, 104]. However, the oxidizing effect of NaOCl may not be compatible with all bonding agents [(81)]. Also, self-etching and self-adhesive systems may perform better than etch-and-rinse systems in the root canal because they are less sensitive to the moist radicular environment [71, 105, 106, 107]. Self-adhesive systems may also result in superior push-out and shear bond strengths of fiber posts and lower polymerization stresses [37, 108, 109]. However, contradictory results were found in other studies [34, 91]. Intracanal air-drying could be more effective than paper points in the removal of solvents and water, resulting in improved push-out bond strength when a self-etching adhesive is used [(110)]. In addition, resin cements that create a thin and uniform film around a well-adapted post are less likely to include voids [90, 92]. The use of an injection delivery cement system or a rotary spiral paste filler may also reduce voids and air entrapment [(111)], resulting in enhanced bond strength of fiber posts to dentin [(109)]. However, these methods should be used only if indicated by the cement manufacturer. Slow-setting cements have the potential to provide stress relief during polymerization [112, 113]. Finally, enhanced light penetration combined with self-activating dual polymerizing adhesives and dual polymerizing resin cements may result in improved polymerization, improved cement properties, and a better bond to dentin [93, 94, 114, 115]. Table 2 presents a summary of studies that discuss the bond to radicular dentin.

Table 2. Summary of Studies: Bond to Radicular Dentin

Author(s)	Year	Materials	Conclusion(s)
Carrigan et al [(73)]	1984	Evaluation of mean number of dentin tubules in different regions of root dentin and in different age groups	Mean number of dentin tubules was less in the apical region of the root canal. Mean number of

Author(s)	Year	Materials	Conclusion(s)
			dentin tubules was less in older individuals.
Tjan and Nemetz (82)	1992	Metallic post cementation with self-etching system after eugenol contamination: noncontaminated, water, water/ethanol, water/ethanol/citric acid, water/ethanol/acetone, phosphoric acid/water, zinc phosphate cement/water	Post retention was decreased when cemented in the presence of eugenol. Irrigation with ethanol restored post retention.
Wakabayashi et al (75)	1993	Evaluation of root canal wall and dentin tubule arrangement	Appearance of calcospherites becomes more frequent toward the apical portion of the root canal wall.
Ngoh et al (79)	2001	Regional bond strength of 2 resin cements to radicular dentin using a eugenol and noneugenol sealer	Microtensile bond strength of resin cement was reduced when a eugenol sealer was used.
Morris et al (81)	2001	Resin cement bond to radicular dentin after NaCl solution, NaOCl, RC-Prep, NaCl/ascorbic acid, NaOCl/ascorbic acid, NaOCl/neutral sodium ascorbate, and RC-Prep/ascorbic acid	Tensile bond strength of resin cement was reduced when NaOCl or RC-Prep was used. Negative effects were reversed with ascorbic acid or sodium ascorbate.
Bouillaguet et al (96)	2003	Composite resin posts cemented with total etch, self-etch adhesive systems, or resin-modified glass ionomer cement, with and without the effect of configuration factor	Microtensile bond strength of resin to dentin was less when cementation was performed in intact canals compared with flat radicular dentin.
Serafino et al (87)	2004	Post space preparation after endodontic treatment: NaOCl, NaOCl/EDTA	Extensive areas of debris, GP remnants, and smear layer were identified in all regions.
Grandini et al (90)	2005	Adhesive cementation of quartz fiber and experimental anatomic posts	In all groups, voids were observed within the cement and between posts and cement.

Author(s)	Year	Materials	Conclusion(s)
Goracci et al (91)	2005	Glass fiber posts cemented with total etch system, self-etch system, or self-adhesive system	Micro–push-out bond strength was greater for the total etch system.
Muniz and Mathias (77)	2005	Adhesive cementation of fiber posts after different irrigant and endodontic sealer combinations: distilled water, NaOCl, AH Plus (Dentsply Maillefer, Tulsa, OK), Endofil (Promedica Dental Material GmbH, Neumuenster, Germany)	Micro–push-out bond strength was reduced when eugenol-based sealer was used. Bond strength values were greater in the apical region.
Baldissara et al (84)	2006	Endodontic treatments: distilled water, NaOCl/ZOE sealer, NaOCl/resin sealer, NaOCl/EDTA/ZOE sealer, NaOCl/EDTA/resin sealer, with and without cycling loading	Micro–push-out bond strength was reduced when eugenol-based sealer was used in cycled groups.
Wrbas et al (34)	2007	Quartz fiber post conditioning methods: silane, untreated Bonding methods: total etch, self-etching, self-adhesive	Tensile bond strength was higher with the use of a total etch system.
Mallman et al (69)	2007	Two types of quartz fiber posts cemented with 2 different adhesive systems	Microtensile bond strength was less in the apical region.
Perdigao et al (70)	2007	Quartz fiber posts cemented in post spaces of varying diameter	Post space diameter did not affect the bond strength.
Faria e Silva et al (114)	2007	Fiber post cementation: translucent quartz fiber post and quartz-coated carbon fiber post	Degree of resin cement polymerization conversion was greater with the translucent fiber post.
Potesta et al (71)	2008	Etching technique after endodontic treatment and post space preparation: acid gel, semigel, low-viscosity gel, liquid etchant, and self-etching primer	Micro–push-out bond strength of composite resin was higher when a self-etching primer was used.
Wu et al (93)	2009	Glass fiber post cementation: different combinations of light-cured self-etching adhesive, dual-cured self-etching adhesive, use of light-guiding attachment, NaOCl	Microtensile bond strength was higher for posts cemented with a light-guiding attachment. NaOCl further improved bond strength.
Radovic et al (115)	2009	Cementation of fiber posts with and without light-transmitting ability	A fiber post with light-transmitting ability resulted

Author(s)	Year	Materials	Conclusion(s)
			in a more continuous, harder, and stiffer cement layer.
Caiado et al (64)	2010	Evaluation of density and cross-sectional area of dentin tubules in deep coronal and radicular dentin after etching treatment	Dentin tubular density was not affected by acid treatment. Cross-sectional area of dentin tubules increased after acid treatment.
Oliveira et al (37)	2011	Glass fiber post conditioning methods: silane, untreated; cemented with self-adhesive cements or total etch system	Shear bond strength was higher for posts cemented with a self-adhesive system compared with a total etch system.
Manicardi et al (74)	2011	Quartz fiber posts cemented with different filling materials: GP/Grossmann sealer, GP/AH Plus, GP/Epiphany, Resilon/Epiphany (Pentron Clinical Technologies, LLC, Wallingford, CT), no filler	Micro–push-out bond strength was not influenced by sealer or region. Coronal region presented denser resin tag formations.
Cecchin et al (98)	2011	Post space treatment before self-etching adhesive cementation: physiologic solution, chlorhexidine, ethanol, chlorhexidine/ethanol; storage up to 12 months	Micro–push out bond strength of fiber posts was preserved with chlorhexidine and/or ethanol pretreatment.
Cecchin et al (100)	2011	Post space treatment before total etch adhesive cementation: physiologic solution, chlorhexidine, ethanol, chlorhexidine/ethanol; storage up to 12 months	Micro–push-out bond strength of fiber posts was preserved with chlorhexidine pretreatment.
Vichi et al (94)	2012	Fiber post cementation: light polymerizing cement, dual polymerizing cement, with or without dual polymerizing adhesive	Polymerization was more effective when a dual polymerizing adhesive agent and a dual polymerizing resin cement were used.
Bergoli et al (108)	2012	Glass fiber post cementation: total etch system, self-etching system, phosphoric acid/self-adhesive cement, self-adhesive system	Micro–push-out bond strength was higher, and polymerization stress was lower when a self-

Author(s)	Year	Materials	Conclusion(s)
			adhesive system was used.
AlEisa et al [85]	2013	Endodontic treatment: eugenol-based and resin-based sealer	Pull-out force of fiber posts was superior when a resin-based sealer was used.
Aleisa et al [105]	2013	Glass fiber post cementation with different adhesive systems	Pull-out force of fiber posts was greater when a self-adhesive system was used.
Wang et al [106]	2013	Glass fiber post cementation: 3-step adhesive, 2-step adhesive, self-etching adhesive, with or without chlorhexidine irrigation	Micro–push-out bond strength of fiber posts was higher with a self-etching adhesive system. Chlorhexidine did not improve immediate bond strength.
Gomes et al [92]	2014	Glass fiber post cementation: well adapted, moderately adapted, poorly adapted	Micro–push-out bond strength was higher for well-adapted posts that formed a thinner cement layer.
Cecchin et al [101]	2014	Post space treatment before adhesive cementation: physiologic solution, chlorhexidine, ethanol, chlorhexidine/ethanol	Micro–push-out bond strength of fiber posts was preserved with chlorhexidine and/or ethanol pretreatment.
Aziz et al [110]	2014	Solvent removal and polymerization methods for glass fiber post cementation with self-etching adhesive: concurrent polymerization of adhesive and cement, separate polymerization of adhesive and cement, intracanal polymerization of adhesive, each method using paper points or intracanal air drying for solvent removal	Micro–push-out bond strength of fiber posts was higher when solvent was removed with intracanal air drying. Polymerization method did not affect bond strength.
Souza et al [111]	2015	Cement delivery for glass fiber post cementation: on post, Lentulo-type spiral, explorer, injection delivery system	Micro–push-out bond strength of fiber posts was higher, and cement had less voids with an injection system.

Author(s)	Year	Materials	Conclusion(s)
Rezende et al [63]	2016	Glass fiber post cementation: dry, wet, overwet radicular dentin	Micro–push-out bond strength was higher when dentin was wet (5 seconds air-drying and 2 paper points).
Aleisa et al [86]	2016	Fiber posts cemented with 3 different luting agents, 24 hours or 2 weeks after obturation; endodontic treatment with eugenol-based sealer	Pull-out force of fiber posts was reduced when the post cementation occurred 2 weeks after obturation.
Kul et al [103]	2016	Irrigation procedure before self-adhesive cementation of glass fiber posts: distilled water, NaOCl/EDTA, chlorhexidine solution, phosphoric acid	Micro–push-out bond strength was higher for posts when the post space was irrigated with NaOCl/EDTA.
Pedreira et al [109]	2016	Glass fiber post cementation: self-adhesive and conventional resin cement; cement applied using manufacturer's instructions or an intracanal delivery system	Micro–push-out bond strength was higher for fiber posts when a self-adhesive system was used with an intracanal delivery system
Simoes et al [104]	2016	Glass fiber post cementation procedure: total etch system, self-adhesive cement, EDTA/self-adhesive cement, phosphoric acid/self-adhesive cement	Micro–push-out bond strength of fiber posts was preserved when a self-adhesive cement with or without EDTA was used.

EDTA, Ethylenediaminetetraacetic acid; GP, Gutta-percha; NaCl, Sodium chloride; NaOCl, Sodium hypochlorite; ZOE, Zinc oxide eugenol.

Microleakage and Degradation of Adhesive Systems

Microleakage is a phenomenon that happens in both adhesive and nonadhesive systems [116, 117, 118] with a gap size of 10–20 μm. Microleakage follows nanoleakage, which occurs in nonvisible gaps within the hybrid layer that have an approximate size of 20–100 nm. Nanoleakage may be the result of incomplete polymerization of the adhesive or the presence of nanometric spaces around the collagen fibers that were not completely infiltrated by the adhesive monomers [119, 120]. These phenomena have been identified in teeth restored with fiber posts in which gaps occur between the dentin and the cement and not between the cement and the post surface [70, 121]. However, they are product dependent [122].

Microleakage results in the presence of water molecules in the adhesive interfaces. Both composite resin materials and fiber posts absorb water over time through a process called diffusion [123]. Water uptake occurs rapidly the first 2 weeks and increases for up to 60 days [124,

[125]. Hygroscopic expansion of composite resin materials may partially counteract polymerization shrinkage stress, which potentially causes the cement to fill shrinkage-related voids or porosities [(126)].

Degradation of the endodontic adhesive systems can be chemical or mechanical [(127)]. Chemical degradation is a direct result of microleakage and is related to the presence of water and enzymes [(127)]. These enzymes can cause hydrolysis of resin components, detachment of resin fillers, and hydrolysis of the exposed collagen fibers [127, 128]. Mechanical degradation is related to the forces that an adhesive interface is subjected to while chewing [(129)]. The materials used in postendodontic adhesive systems exhibit different moduli of elasticity, causing stress concentration at the various interfaces when the endodontically treated tooth is subjected to functional loads [(12)]. Separation and micromovement between different bonded materials may follow when the adhesive interface degrades [(130)]. Further leakage and caries are expected as a consequence of micromovement between the components [(131)]. In addition, thermal changes occur and can induce further stress through thermal contraction and expansion of the materials at the adhesive interfaces because of differences in the coefficient of thermal expansion [132, 133]. Thus, the chance of failure increases as the number of participating interfaces increases [134, 135, 136].

The survival and long-term success of endodontically treated teeth with posts are affected by many different factors. There is no evidence to indicate whether the success in bonding is directly correlated to the clinical success of the treated tooth. However, bonding is necessary when fiber-reinforced posts are used [(11)]. Despite the unfavorable environment for bonding in the root canal system and the many limitations of the techniques and materials used for bonding, successful clinical outcomes are reported in the literature in teeth restored with posts [137, 138, 139, 140]. Furthermore, fiber post placement in anterior teeth may increase fracture resistance and subsequently improve tooth survival, especially when the teeth are structurally compromised [141, 142, 143, 144].

Conclusions

Adhesive cementation of endodontic posts is a popular treatment option because of improved retention. Although a post–endodontic adhesive interface finds application in the theoretically sound cohesive endodontic units, the bond between the endodontic post and the prepared root canal could be easily jeopardized. There are potential limitations in the development of a predictable bond between composite resin materials and both fiber and metallic posts. Additionally, successful adhesion to radicular dentin may be hindered by factors related to the morphology of the dentinal tissue, the materials used during endodontic treatment, the technique for adhesive cementation of the endodontic post, and the geometric characteristics of the root canal space. Further microleakage and degradation phenomena that occur in the complexity of the oral environment may further compromise the post–endodontic adhesive interface. On the other hand, bonding between the adhesives and the post and between the adhesives and the dentin may be enhanced through various post surface treatments and careful selection of root canal irrigants and adhesives. Table 3 summarizes clinical actions that could result in an enhanced bond to radicular dentin. However, any conclusions should be drawn with caution because there are no clinical studies addressing the bonding potential of endodontic posts to radicular dentin. Existing knowledge is vastly based on *in vitro* studies and a few systematic reviews of *in vitro* studies. Future clinical studies will provide some guidance in selecting the optimal bonding system for endodontic posts.

Table 3. Factors Potentially Affecting Bond Quality to Radicular Dentin and Suggested Actions

Factors affecting bond quality	Suggested actions
Endodontic treatment related	
Chemomechanical preparation materials containing peroxides and glycol	Ascorbic acid/sodium ascorbate may reverse oxidizing effects
NaOCl	
Eugenol-based sealers	Pretreatment with ethanol
	Use of resin-based sealers
Post space preparation related	
Smear layer containing sealer and GP remnants	EDTA and NaOCl may eliminate the smear layer more efficiently
Post cementation related	
Inadequate etchant removal	Use of self-adhesive systems
Moisture control	Radicular dentin should be slightly moist
	Intracanal air-drying may be more effective than paper points
	Self-etch and self-adhesive systems are less sensitive to moisture
Incomplete monomer penetration	Pretreatment with ethanol may allow better monomer penetration
Cement voids	A well-adapted post creates a thinner cement layer with less voids
	Use of an injection system or rotary spiral for cement delivery
Incomplete light penetration, polymerization	Use of translucent posts with dual polymerizing adhesives and dual polymerizing resin cements
Geometric	
Configuration factor, resin polymerization contraction	Self-adhesive systems may result in lower polymerization stress
	Slow-setting cements may provide polymerization stress relief
	Hygroscopic expansion of resin cements may compensate for shrinkage stresses
Degradation	

Factors affecting bond quality	Suggested actions
Dental MMPs	Chlorhexidine pretreatment may inhibit MMP-related degradation
Moduli of elasticity differences	
Coefficients of thermal expansion differences	

GP, gutta-percha; MMP, matrix metalloproteinase; NaOCl, sodium hypochlorite.

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