Foundation restorations in fixed prosthodontics: Current knowledge and future needs

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Purpose. The Ad Hoc Committee on Research in Fixed Prosthodontics established by the Academy of Fixed Prosthodontics publishes a yearly comprehensive literature review on a selected topic. The subject for this year is foundation restorations.
Methods. Literature of various in vitro and in vivo investigations that included technical and clinical articles was reviewed to provide clinical guidelines for the dentist when selecting methods and materials for restoration of structurally compromised teeth. Topics discussed and critically reviewed include: (1) desirable features of foundation restorations, (2) foundations for pulpless teeth, (3) historic perspectives, (4) cast posts and cores, (5) role of the ferrule effect, (6) prefabricated posts, (7) direct cores, (8) foundation restorations for severely compromised teeth, (9) problems and limitations, (10) future needs, and (11) directions for future research.
Conclusion. This comprehensive review brings together literature from a variety of in vitro and in vivo studies, along with technique articles and clinical reports to provide meaningful guidelines for the dentist when selecting methods and materials for the restoration of structurally compromised teeth. (J Prosthet Dent 1999;82:643-57.)

CLINICAL IMPLICATIONS

The topic of foundation restorations involves many materials and techniques used in everyday dental practice. This article comprehensively reviews the dental literature on this subject to provide clinically relevant guidelines for the dentist. Limitations in knowledge are discussed, and suggestions for future research to improve the profession's understanding of the clinical performance of foundation restorations are made.

The Ad Hoc Committee on Research in Fixed Prosthodontics established by the Academy of Fixed Prosthodontics is dedicated to sustaining academic excellence and interest in fixed prosthodontics. The goal of the committee is to disseminate knowledge relevant to fixed prosthodontics with a yearly publication of a comprehensive literature review on a selected topic. The subject for this year is foundation restorations.

PURPOSES OF FOUNDATION RESTORATIONS

Successful fixed prosthodontic treatment depends on the ability of cemented cast restorations to resist dislodgment from tooth preparations. The interaction of 3 primary factors appears to influence potential for dislodgment: (1) design of the tooth preparation, (2) fit of the casting, and (3) nature of the cement. This review will concentrate on methods to improve the design of tooth preparations for structurally compromised teeth by using foundation restorations.

Tooth preparations must possess retentive and resistance form to ensure long-term serviceability of fixed prosthodontic restorations. Retention will prevent dislodgment of a casting along a path parallel to the path of insertion of a restoration and resistance will prevent dislodgment along any other path (Fig. 1). The dentition is subjected to a 180-degree field of force vectors (Fig. 2), so resistance form is considered to be more critical than retentive form. However, it is impossible to separate these 2 features.[1,2]

Resistance has been associated with the degree of taper of a tooth preparation.[3] Wiskott et al[2] suggested a linear relationship between height or diameter of the preparation and resistance. Grooves have also been shown to enhance the resistance form especially in molars,[4] and a recent clinical study of cast restorations indicated a lack of resistance form to the tooth preparations of dislodged castings.[5]

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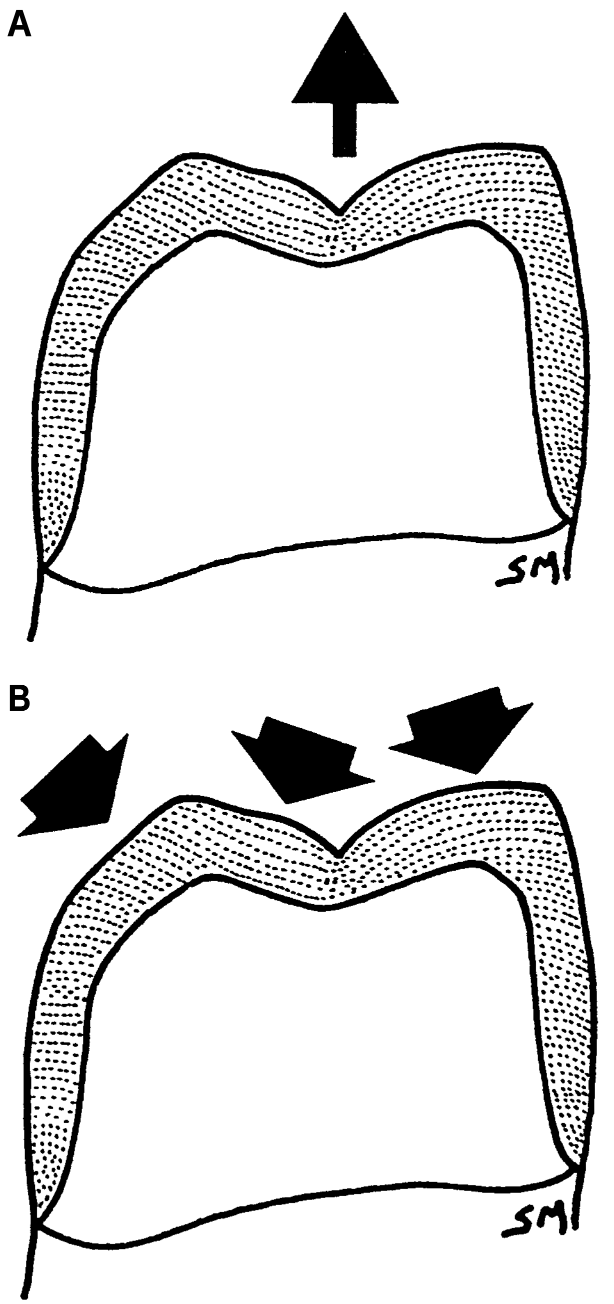

Fig. 1. A, Retention prevents dislodgment of restoration along path of insertion. B, Resistance prevents dislodgment of restoration by forces directed in apical, oblique or horizontal direction.

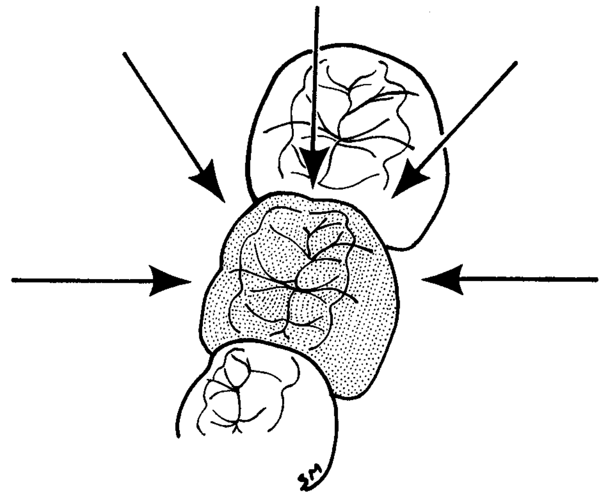

Fig. 2. During function, artificial crown is subjected to 180-degree field of force vectors.[2]

It is the responsibility of the dentist to incorporate retention and resistance form in the design of the tooth preparation that will receive a cast restoration. Nevertheless, cast restorations are commonly placed on damaged teeth with substantial loss of tooth structure. Retention and resistance form became compromised as the height of the prepared tooth is reduced in relation to the width of the preparations and overall height of the final cast restoration.[6] A foundation restoration made from a restorative material is often indicated when inadequate coronal tooth structure remains to permit development of retentive and resistance form.

Shillingburg et al[7] advocated the placement of a core reconstruction or foundation restoration when one half or more of the coronal tooth structure is missing, and pins can be used to augment the retention of the foundation restoration.[8] After the restorative core material is secured, the tooth with its core reconstruction can be prepared following accepted guidelines for tooth preparations of intact teeth.[9]

DESIRABLE FEATURES OF FOUNDATION RESTORATIONS

Foundation restorations replace coronal tooth structure that was lost as a result of dental caries, previous restorations or tooth fracture and may be fabricated from various restorative materials. The desirable features of the foundation restoration vary depending on clinical conditions.

Minute depressions or undercuts may be present in a tooth preparation. If adequate retentive and resistance form can be developed from natural tooth structure, strength of the foundation restoration is less critical, and these minor irregularities can be restored with the adhesive restorative materials such as glass ionomer, resin-modified glass ionomer, or compomer cements.[10] A foundation restoration that does not contribute to the overall retention and resistance form of the tooth preparation is commonly described as a base. When the foundation restoration augments the retention and resistance provided by the remaining tooth structure, it is usually described as a core reconstruction.

Physical properties of a core reconstruction become more important as residual intact tooth structure decreases.[10] Some desirable features of a core material include adequate compressive strength to resist intraoral forces,[11] sufficient flexural strength to prevent flexure of the core during normal intraoral functions,[11] biocompatibility,[12] resistance to leakage of oral fluids at the core / tooth interface,[13,14] ease of manipulation,[15] ability to bond to remaining tooth structure,[16-18] thermal coefficient of expansion and contraction similar to tooth structure,[13] dimensional stability,[19] minimal potential for water absorption,[20-22] and inhibition of dental caries.[23]

When retentive and resistance features are derived primarily from the core material, the strength of a foundation restoration and the retention of a core can directly influence survival of the artificial crown. Certain core materials may lack the inherent strength to support a complete crown. A tooth that must serve as an abutment to a fixed or removable prosthesis is subjected to increased stress, and the overall mechanical properties of the core must be adequate to resist these forces. Posterior teeth will be exposed to higher force thresholds than anterior teeth and the direction of the force differs. Therefore, required compressive and flexural strength may differ, depending on the location of the tooth in the dental arch. In addition, a foundation restoration that supports a translucent all-ceramic crown should not adversely effect the esthetic qualities of the final restoration.[24]

FOUNDATION RESTORATIONS FOR PULPLESS TEETH

Historical perspectives

The concept of using the root of a tooth for retention of a crown is not new.[25] In the 1700s Fauchard inserted wooden dowels in canals of teeth to aid in crown retention.[26] Over time the wood would expand in the moist environment to enhance retention of the dowel until, unfortunately, the root would often fracture vertically.[25] Additional efforts to develop crowns retained with posts or dowels in the 1800s were limited by the failure of the “endodontic” therapy of the era. Several of the 19th century versions of dowels also used wooden “pivots,” but some dentists reported the use of metal posts favored by Black[27] in which a porcelain-faced crown was secured by a screw passing into a gold-lined root canal. A device developed by Clark in the mid-1800s was extremely practical for its time because it included a tube that allowed drainage from the apical area or the canal.[28]

The Richmond crown was introduced in 1878 and incorporated a threaded tube in the canal with a screw-retained crown. The Richmond crown was later modified to eliminate the threaded tube and was redesigned as a 1-piece dowel and crown.[29,30] One-piece dowel-crowns became unpopular because they were not practical. This was evident when divergent paths of insertion of the post-space and remaining tooth structure existed, especially for abutments to fixed partial dentures (FPDs). One-piece dowel-crown restorations also presented problems when the crown or FPD required removal and replacement. These difficulties led to development of a post-and-core restoration as a separate entity with an artificial crown cemented over a core and remaining tooth structure.

With the advent of scientific endodontic therapy in the 1950s, the challenges increased for restorative dentistry. Teeth that were commonly extracted without hesitation were successfully treated with predictable endodontic therapy, and a satisfactory restorative solution was necessary, especially for teeth with severe damage. Cast posts and cores became routine methods for restoration of endodontically treated teeth.

CAST POSTS AND CORES

The development of cast dowel cores was a logical evolution from the Richmond crown. For endodontically treated anterior teeth with moderate to severe destruction, cast posts and cores have been described as the restorative method of choice.[31] Conversely, molars often perform satisfactorily with direct cores retained by engaging the pulpal chamber and a portion of the root canals,[32,33] and retention of the core can be augmented by placement of 1 or more prefabricated intraradicular posts. Premolars may be restored with either custom cast posts and cores or prefabricated post(s) with direct cores.

Methods of fabricating cast posts and cores

A reliable method for fabricating a custom dowel core is direct fabrication of the pattern.[34] The tooth is prepared for the crown after the existing restorations, dental caries, and weakened tooth structure are removed; the post space is then prepared. Guidelines for the length of the post include a length equal to the length of the clinical crown of the final restoration,[35] and two thirds or three quarters the length of the root in bone.[36] In vivo studies have suggested that clinical success of posts is directly proportional to their lengths; so it is rational to prepare a post channel as long as it is consistent with anatomic limitations while maintaining 4 to 5 mm of apical gutta percha seal.[37-40] A shorter post is undesirable because it is less retentive and can produce unfavorable leverage and shear stresses within the root canal that may predispose the root to fracture.[41,42] The width of the post is also an important consideration because arbitrarily widening the diameter of the post will reduce the thickness and strength of the radicular dentin.[43] Thickness of remaining dentin is critical.

The post space should provide resistance to rotation of the dowel core. If the configuration of the prepared canal is circular in cross section, it will not provide this resistance to rotation. A keyway should be placed within the canal.[44] A positive seat for the core at the opening of the post-space is desirable to prevent overseating of the dowel, which may wedge the root and cause vertical fracture.[44]

Numerous materials have been described for fabrication of the dowel-core pattern. These materials included: wax with a plastic rod as a carrier and support,[34,36,45] wax with a dental bur,[44] and acrylic resin with a solid plastic sprue.[35,46-49] Another method developed a core of acrylic resin with an endodontic file coated with wax that adapted to the prepared canal.[50] A variation of the direct custom dowel core incorporated a prefabricated plastic pattern manufactured to correspond to the diameter and configuration of a specific reamer. With this method, the desired reamer was used to instrument the canal, and the matching plastic pattern was inserted into the post channel. Acrylic resin was then adapted to the coronal surface of the post pattern and contoured to the desired form. These prefabricated plastic patterns can be divided into 2 types: (1) precision parallel dowels and (2) precision tapered dowels.

Custom cast dowel cores require 2 visits. A primary disadvantage of the direct method of fabricating posts and cores is the chair time to fabricate the pattern. The indirect method conserves chair time by delegating the pattern for the post and core to a dental laboratory technician. Nevertheless, an accurate impression of the prepared post space that extends deeply in the canal of an endodontically treated tooth is a challenge. Success of the indirect method depends on the accuracy of the impression replicating the internal surface of the prepared root canal. Impression material may be injected in the post space and distributed by a spiral paste filler to capture the internal morphology of the canal.[51] A rigid object is inserted in the canal before the initial set of impression material to strengthen this impression and minimize potential for distortion. Suggested reinforcement mechanisms include toothpicks,[52] wire,[53,54] paper clips,[55,56] and plastic sprues.[57]

Prefabricated precision metal posts[58] and fit-sized plastic patterns[59] offer an alternative approach that uses a pick-up impression. The post space is prepared with the appropriate instruments to conform to the preselected pattern, and the pattern is inserted in the canal with a substantial extension beyond the coronal tooth finish line. An impression is made that picks up the pattern that is transferred to the working cast, and the dowel core can be fabricated by a dental laboratory technician.

Alloys for cast posts and cores

Traditionally, custom dowel cores were cast in a gold alloy comparable to the alloys used for complete crowns. For decades the US government maintained a gold standard that resulted in a fixed, inexpensive price for gold. When this regulation for the price of gold was removed, the cost of gold elevated dramatically in the 1970s. With the cost of gold at unprecedented levels, there was an incentive to develop alternative alloys for cast restorations, and included dowel cores. Base metal alloys traditionally used to cast frameworks for removable partial dentures (RPDs) were suggested as logical alternatives to gold alloys, and their use for dowel cores was advocated.[47,60] A major disadvantage of base metal alloys was their hardness because these castings were ground and contoured chairside. Alternative alloys were later introduced to resolve the problems of contouring and finishing posts and cores fabricated from base metal alloys. Dowel cores made from silver-palladium alloys were more easily adjusted chairside and were suitable castings.[61] Many properties of these silver-palladium alloys are similar to those of gold casting alloys, and they offer an economical and satisfactory alternative for custom-cast posts and cores.

Cast posts and cores as a method of restoring pulpless teeth

Cast dowel cores have been reported to provide excellent service for endodontically treated teeth with moderate-to-severe damage. A 6-year retrospective study of 96 endodontically treated teeth with extensive loss of tooth structure and restoration with the use of cast dowel cores indicated a 90.6% success rate.[62] Cast posts are best applied to single-rooted teeth, especially incisors and canines; and the use of custom cast dowel cores, fabricated directly or indirectly, remains an integral component of prosthodontic treatment. A recently reported national survey investigated dentists' philosophies and techniques of restoring endodontically treated teeth. The results indicated that the majority of dentists in the United States used either cast posts exclusively or both cast posts and prefabricated posts in their practices.[63]

ROLE OF THE FERRULE EFFECT

A post and core in a pulpless tooth can transfer occlusal forces intraradicularly with resultant predisposition to vertical fracture of the root.[64,65] The role of the final cast restoration in protection of the dowel-restored pulpless tooth has been discussed for decades. In 1959 Frank[66] indicated the importance of protective coronal coverage of pulpless teeth, and Rosen[44] suggested that the "hugging action" of a subgingival collar of cast metal provided extracoronal bracing that could prevent fracture of tooth structure. Eissman and Radke[67] used the term *ferrule effect* to describe this 360-degree ring of cast metal and recommended extension of the definitive cast restoration at least 2 mm apical to junction of the core and remaining tooth structure (Fig. 3).

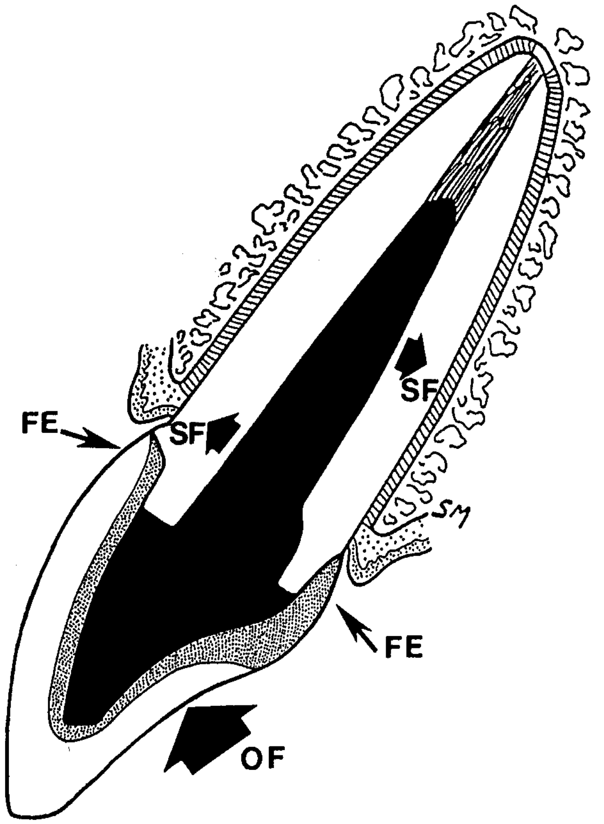

Fig. 3. Occlusal forces (*OF*) are transmitted to center of root through post as spreading forces (*SF*) that can cause vertical fracture of root. If artificial crown extends 2 mm apical to junction of core and tooth, ferrule effect (*FE*) will resist these spreading forces. Post and core in combination with artificial crown provide coronoradicular stabilization.

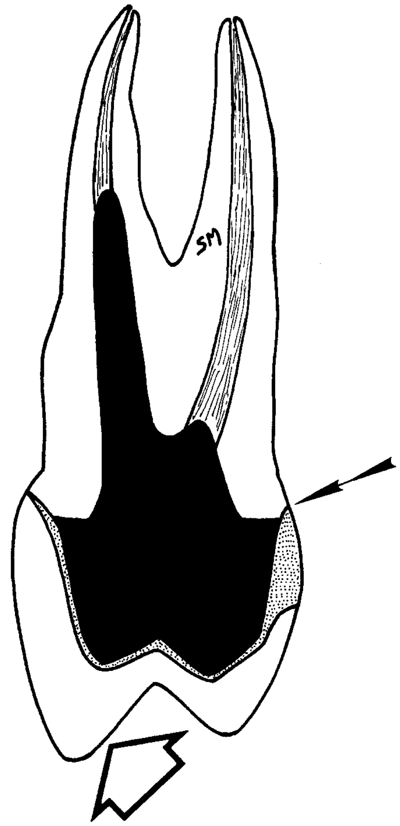

Fig. 4. Pulpless maxillary first premolar with post in buccal root. Occlusal force (*large arrow*) can produce tensile stresses at lingual aspect of crown margin (*small arrow*) that may jeopardize integrity of marginal seal of crown.

In vitro studies by Barkhorder et al[68] and Hemming et al[69] reported an improved resistance to fracture when encircling collars or ferrules were used with posts. Assif et al[70] examined in vitro the effect of post design on the fracture resistance of pulpless premolars restored with cast crowns. Their results indicated that the design of the post did not influence resistance to fracture if the core was covered with a complete cast crown that extended 2 mm apical to the finish line of the core. An in vitro study by Isidor et al[71] evaluated the effects of post length and ferrule length on the resistance to dynamic loading of bovine teeth restored with artificial crowns. Resistance to failure was greatest for the group restored with a combination of the longest posts (10 mm) and the longest ferrules (2.5 mm).

Libman and Nicholls[72] evaluated in vitro the effects of ferrules on the integrity of the cement seal of cast crowns, and reported improved resistance to fatigue failure of the cement seal of a crown when the crown margin extended at least 1.5 mm apical to the margin of the core. Another study indicated that failure of the cement seal of the artificial crown occurred first on the tension side of the tooth, especially when the ferrule was small and the post was off-center (Fig. 4).[73] Loss of the cement seal of the coronal restoration is insidious and clinically undetectable initially. Nevertheless, leakage will occur between the crown margin and the tooth surface and may extend into the post space, which could lead to dental caries and potential loss of the tooth.[74] A clinical study by Torbjörner et al[75] retrospectively evaluated the survival and failure characteristics of teeth restored with posts and artificial crowns, and their results indicated a higher potential for fracture of the post when the cemented crowns did not provide a ferrule effect (Fig. 5).

Cementation of a post with a dentinal bonding system could theoretically provide internal bracing of the root that substitutes for the extracoronal ferrule. Two recent in vitro studies have suggested this possibility.[76,77] Clinical studies to corroborate the internal reinforcement of roots with dentinal bonding systems are lacking. Thus, there is no compelling evidence to suggest abandonment of the classic extracoronal ferrule.

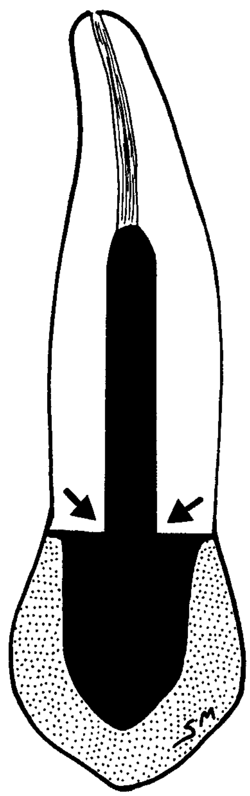

Fig. 5. When ferrule is absent, occlusal forces are concentrated at junction of post and core, and post may fracture.

Shillingburg et al[78] have advocated a contrabevel in the tooth preparation for a cast post and core to produce a core with a collar that serves as a secondary ferrule, independent of the ferrule provided by the cast crown. However, Sorensen and Engleman[79] reported no advantage to this contrabevel and collar when a crown was cemented over the core. Their results indicated that the ferrule effect was obtained from nearly parallel walls of intact tooth structure coronal to the finish line for the artificial crown and not from the contrabevel on the core preparation.[79] They also reported that a 1-mm beveled finish line for a complete crown preparation without additional tooth structure coronal to the bevel did not improve the fracture resistance of the root.[79] Loney et al[80] conducted an analysis of stresses developed in photoelastic-resin models of maxillary canines restored with cast cores. Half the specimens contained cores with a 1.5-mm collar to provide a ferrule as a component of the core itself, and half omitted this collar. Their results indicated substantially higher mean stresses with the collared cores and suggested that incorporation of a ferrule with a cast core may be undesirable.

Milot and Stein[81] investigated the ability of beveled tooth preparations to improve the resistance to fracture of plastic tooth analogs restored with three different post systems. Substantial tooth structure remained coronal to a rounded-shoulder finish line for complete crowns, and a 1-mm bevel was added to half the specimens. The results of their in vitro study indicated an appreciable increase in mean failure thresholds when the length of the ferrule was increased by the addition of a 1-mm bevel to the finish line.[81]

Despite the well-intended recommendation to develop a cast ferrule as a component of the cast core, there is little evidence to support the contrabevel and ferrule as integral components of a cast core.[39,82] Preparation of a contrabevel for the core requires the removal of sound coronal tooth structure and may compromise the ferrule effect from the cemented artificial crown. This design to the post-and-core preparation also results in a final casting with both intracoronal and extracoronal components, which complicates compensation for thermal contraction of the alloy during investing and casting. Finally, this ferrule as a part of the cast core cannot be developed with any of the direct core materials. However, failure of teeth restored with direct core reconstructions has not been associated with the lack of a ferrule effect from the core material when the cemented artificial crown provides a ferrule.

Current knowledge has confirmed that the dentist should retain as much coronal tooth structure as possible when preparing pulpless teeth for complete crowns to maximize the ferrule effect. A minimal height of 1.5 to 2 mm of intact tooth structure above the crown margin for 360 degrees around the circumference of the tooth preparation appears to be a rational guideline for this ferrule effect. Surgical crown lengthening[83] or orthodontic extrusion[84] should be considered with severely damaged teeth to expose additional tooth structure to establish a ferrule. If these provisions for developing a ferrule are impractical, extraction of the tooth and replacement with conventional or implant-supported prosthodontics should be considered.

PREFABRICATED POSTS

Prefabricated posts have become more popular, and there is a variety of systems available. A recent nationwide survey of dentists indicated that 40% of general dentists used prefabricated posts most of the time, and the most popular prefabricated post was the parallel-sided serrated post.[63] The use of prefabricated posts with a direct core reconstruction is often regarded as the restorative method of choice for restoration of pulpless molars with substantial loss of tooth structure.[31] These commercially available posts are supplied in various shapes with numerous surface configurations. They may be parallel-sided or tapered. Some parallel-sided posts are tiered, whereby parallelism is maintained but their diameters are narrowed in their apical portions where the root is generally thinner. Some prefabricated posts are passive, and others actively engage tooth structure with threads.[85,86] Active posts are more retentive, but can generate unfavorable stresses and predispose the root to fracture.[87-89] The most retentive passive post is a long, parallel-sided post with a roughened surface, but a parallel-sided post will often require removal of substantial radicular dentin to achieve the desired length.[39,41,90-92]

Carbon-fiber reinforced epoxy resin posts

Most prefabricated posts are metallic, but there are several newer nonmetallic systems available. A post fabricated from a carbon-fiber reinforced epoxy resin was developed in France by Duret and Renaud, and became commercially available in Sweden in 1992.[93] Carbon-fiber reinforced epoxy resin is a recently introduced dental restorative material composed of unidirectional carbon fibers that are 8 μm in diameter embedded in a resin matrix and supporters claim the physical properties are similar to those of natural dentin.[94-99] The material is radiolucent and appears to be biocompatible based on cytotoxicity tests reported by Torbjörner et al.[99]

Two in vitro studies have indicated that these carbon-fiber posts possessed inferior strength compared to metal posts.[100,101] Nevertheless, an in vitro study of carbon-fiber reinforced epoxy resin posts that used bovine teeth suggested that these posts were less likely than metal posts to cause fracture of the root at failure.[102] A retrospective short-term clinical study of 236 teeth restored with carbon-fiber reinforced epoxy resin posts reported no failures attributable to the posts after a period of 2 to 3 years of service.[103] These posts are manufactured in several configurations (Fig. 6) and are used with composite cores and resin luting agents. Nevertheless their ability to bond to adhesive dental resins appears unremarkable, and their bond can be improved with mechanical retention such as serrations.[98,104]

At this time the long-term effects of restoring pulpless teeth with these posts are unknown. Although the stiffness of these posts has been reported to be similar to human dentin, Purton and Payne[98] reported a transverse modulus of elasticity for these posts that exceeded the values recorded for stainless steel posts. Because of the parallel arrangement of the reinforcing carbon fibers, these posts displayed anisotropic behavior whereby their physical properties differ depending on the loading angles.[98] Furthermore, even if the elastic modulus of the post were comparable to human dentin, this property will not ensure similar clinical behavior for the post and radicular dentin. The root is essentially a hollow tube, and the thin rod-shaped post is within this hollow tube surrounded by an intervening layer of composite resin luting agent. The radically different configurations of the root compared with the post combined with the interposed composite resin luting material suggest that the flexibility of the post will not match the flexibility of the root. Another in vitro study indicated that the form of the post would influence its rigidity and reported that smooth posts were less flexible than serrated posts.[104]

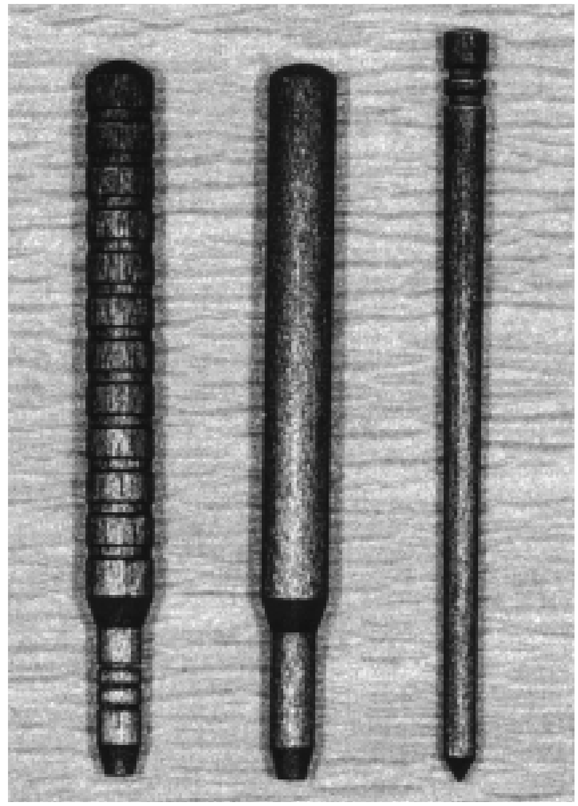

Fig. 6. Various configurations of commercially available carbon-fiber reinforced epoxy resin posts.

A flexible post can be detrimental especially when there is little remaining natural tooth structure between the margin of the core and the gingival extension of the artificial crown. When the ferrule is absent or extremely small, occlusal loads may cause the post to flex with eventual micromovement of the core, and the cement seal at the margin of the crown may fracture in a short time (Fig. 7). Marginal leakage with recurrent dental caries will ensue, but the deterioration will be unnoticed until substantial destruction of tooth structure occurs.[74]

Zirconia posts

With recent advances in ceramic technology, the all-ceramic crown has become more popular. However, restoring a pulpless tooth with a metal post and core in combination with an all ceramic crown is a challenge. The underlying metal from the post and core can alter the optical effects of a translucent all-ceramic crown and compromise the esthetics.

In response to the need for a post that possesses optical properties compatible with an all-ceramic

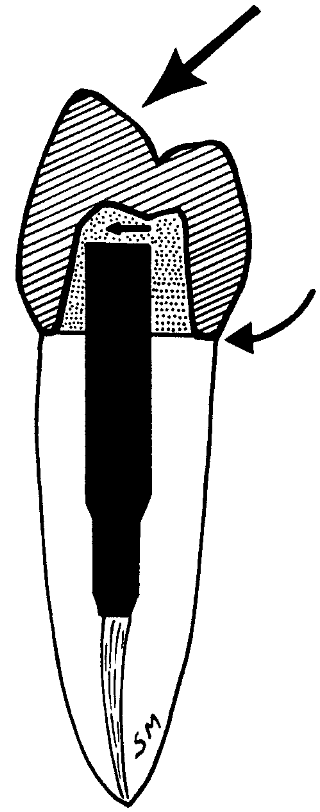

Fig. 7. Flexible post may allow micromovement of core (*small arrow*) under occlusal load (*large arrow*) when ferrule is small or absent with resultant fracture of cement seal at crown margin (*curved arrow*).

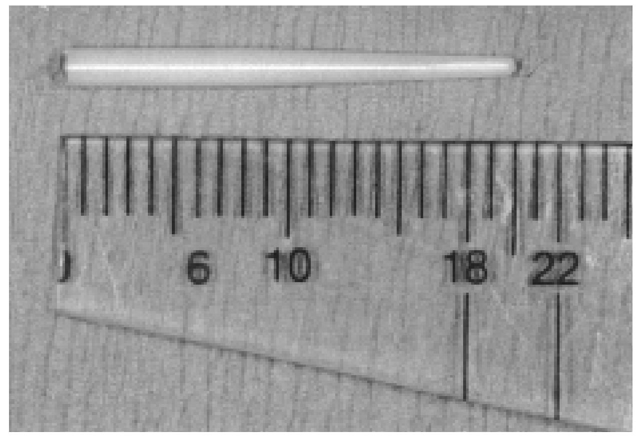

Fig. 8. Commercially available post made from zirconium oxide.

crown, an all-ceramic post has been developed (Fig. 8).[24,105-108] This post is composed of zirconium oxide, a material that has been used in medicine for orthopedic implants. Animal studies have indicated stability after long-term aging of this ceramic material without evidence of degradation.[109,110] The post is made from fine-grain, dense tetragonal zirconium polycrystals (TZP),[111,112] and the zirconia post has been reported to possess high flexural strength and fracture toughness.[113] This radiopaque material is biocompatible with some physical properties similar to steel.[113-115] The zirconia post was designed for use with an adhesive resin cement, and one in vitro study has recorded poor resin-bonding capabilities of this post to radicular dentin after dynamic loading and thermocycling.[116]

These posts were also designed for use with a composite core material, but a large composite core may not be sufficiently rigid to support a brittle all-ceramic crown.[11,20] Sorensen[24] described a method of combining this post with IPS Empress pressed-glass technology to compensate for the disadvantages of a composite core for an all-ceramic restoration. A custom glass-ceramic core was formed over the prefabricated zirconia post to develop a post and core that was entirely ceramic.

Clinical trials are lacking with this new all-ceramic post, and the ability of these posts to resist intraoral forces are unknown. Ceramics are tough materials with high compressive strengths, but are brittle when subjected to shearing forces.[117,118] An alternative to this all-ceramic post is a cast post and core made from a metal ceramic alloy. Opaque porcelain can be fused to the core portion to provide a durable post and core that will disguise the graying effect that can occur with conventional cast metal posts and cores when combined with all-ceramic crowns.[119]

Woven-fiber composite materials

The manufacturer of a cold-glass plasma-treated polyethylene woven-fiber has suggested this material in a resin composite to provide coronoradicular stabilization for pulpless teeth.[120,121] The fibers are multidirectional and developers of the material have suggested a number of uses.[122] An in vitro study of this material with extracted human teeth indicated that woven-fiber composite posts and cores were significantly weaker than cast metal posts and cores.[123] Nevertheless, when this woven-fiber composite was reinforced with a smaller-diameter prefabricated post, the strength of the system increased significantly.[123] These prefabricated posts embedded in the woven-fiber composite were not as strong as cast posts and cores, but were less likely to cause fracture of the roots when subjected to failure loads.[123]

CEMENTS AND CEMENTATION OF POSTS

Dental cements

Dental cements lute the post to radicular dentin, and properties such as compressive strength, tensile strength, and adhesion of the cement are commonly described as predictors for success of a cemented post. Other factors such as potential for plastic deformation, microleakage, water imbibition, behavior of the cement during the setting process, and handling characteristics can also influence the survival rate of a cemented post.

There are several luting agents currently available to the dentist and they include: zinc phosphate, polycarboxylate, glass ionomer, resin-modified glass ionomer, compomer, and resin cements. These different classes of cements represent a variety of products by a number of dental manufacturers. There are distinct advantages and inherent disadvantages to each product.

Zinc phosphate cement is the standard cement used for decades to lute dental restorations, and this cement has been extremely successful. The primary disadvantages of zinc phosphate cement are solubility in oral fluids and lack of true adhesion. Polycarboxylate and glass ionomer cements provide a weak chemical bond to dentin.[124,125] Polycarboxylate cements have been reported to undergo plastic deformation after cyclic loading and may be less retentive than zinc phosphate and glass ionomer cements.[126] Glass ionomer cement has been reported to release fluoride[127-129]; nevertheless the ability of glass ionomer cement to inhibit dental caries in dentin has not been clearly demonstrated.[130] Resin-modified glass ionomer cements possess similar chemical properties and also can leach fluoride[131,132]; however, objective proof of the clinical benefit of this fluoride release is also lacking.[133] Adhesive resins are essentially insoluble and provide better retention in vitro compared with nonadhesive resins and conventional cements.[134]

There are peculiarities to the handling characteristics and clinical behavior of each class of cement. Glass ionomer cement requires several days[135] or even several weeks[136] to reach its maximal strength, so it is unsuitable as a luting agent for posts. Any recontouring of the core with a dental handpiece soon after cementation of the post will cause vibration of the post that may weaken the immature cement film and contribute to eventual retentive failure of the post.

Resin-modified glass ionomer cement has become popular for cementation of complete crowns, and its use has been suggested for cementation of posts.[137,138] However, this class of cement imbibes water and expands with time,[139,140] and there is anecdotal evidence that volumetric expansion of this cement will fracture all-ceramic crowns relatively soon after cementation.[141] If this cement can fracture all-ceramic crowns, its expansion will likely cause vertical fracture of roots if selected to cement posts. Therefore, it appears at this time that resin-modified glass ionomer cements should be avoided for cementation of posts.

Resinous cements have been studied extensively, and several investigations have evaluated the ability of adhesive resins to retain intraradicular posts. Some studies have reported significantly greater retention for posts cemented with adhesive resins,[142-145] whereas others have reported conflicting results.[146-148] One factor that has a detrimental effect on resinous cements is eugenol contamination of dentin. The setting process of dental resins occurs by free-radical addition polymerization, and this process can be inhibited by phenolic compounds, such as eugenol (2-methoxy-4-allyphenol).[146] Most endodontic sealers contain eugenol, and the obturation of the root canal occurs by condensation of the gutta percha filling material under pressure to force the eugenol-containing liquid sealer into the dentinal tubules and lateral canals. After eugenol has penetrated dentin, it is difficult to remove, and the presence of eugenol in the radicular dentin can explain the inconsistent results reported for posts cemented with adhesive resins.[142,146,148,149]

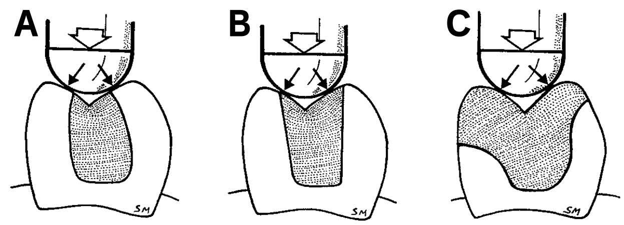

Fig. 9. Study of pulpless premolars restored with MOD silver amalgam restorations (**A**), resin-bonded MOD inlays (**B**), and MOD onlays cemented with zinc phosphate cement (**C**) indicated best fracture resistance with onlays.

The ability of resins to bond to dentin and restorative materials can enhance retention, but this increased retention may not ensure resistance to dislodgment of the post with normal clinical conditions. One study has reported extremely high retentive values for an unfilled 4-META resinous cement,[142] but this cement is relatively weak and has been reported to undergo plastic deformation that will likely lead to fatigue failure in vivo.[150] Adhesive resin cements are also technique sensitive, and Mendosa and Eakle[147] have reported difficulty in manipulating a resinous cement in vitro. For example, some posts did not seat completely in their post channels because of premature setting of the resin.

Resin cements have also been suggested as a method to reinforce pulpless teeth. One study evaluated the ability of inlays cemented with resin bonded procedures in posterior pulpless teeth to bond together the remaining tooth structure and eliminate the need to cover and surround the cusps with a cast restoration. This study compared the fracture resistance of extracted endodontically treated premolars restored with MOD silver amalgam restorations, resin-bonded MOD inlays, and MOD onlays cemented with zinc phosphate cement (Fig. 9). The greatest resistance to fracture was

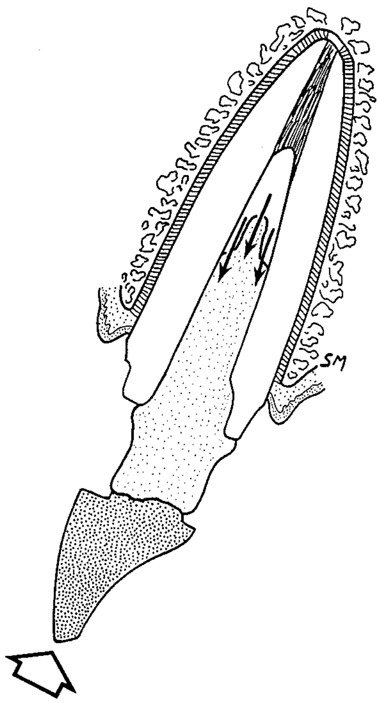

Fig. 10. Cement was placed on post only. As post is seated (*large arrow*) entrapped air within canal (*small arrows*) escapes through liquid cement, creating voids in cement film.

recorded for MOD onlays cemented with zinc phosphate cement.[151]

Cementation of posts

If cement is placed on the post only when it is cemented, air will be trapped deeply in the prepared canal, and as the post is seated the air will travel through the liquid cement to create voids that will compromise the physical properties of the cement film (Fig. 10). Filling the canal with cement before seating the post will avoid air entrapment and ensure a dense uniform cement lute.[152] Nevertheless few dental cements provide adequate working time to introduce cement into the canal before the post is seated, and resin cements are especially prone to premature setting if this procedure is attempted. Tjan et al[146] have demonstrated substantial voids with an adhesive resin cement, and suggested that these voids were responsible for the unexpected low retentive values for posts luted with the resin cement. Zinc phosphate cement is especially well suited for placement of the cement in the canal before seating of the post because of its extended working time.[152]

To date, there have not been any long-term clinical trials of cemented posts that demonstrate the superiority of a specific cement, and most dentists will select a cement empirically. Studies have confirmed that none of the available cements possess physical properties that are capable of compensating for problems commonly associated with a poorly designed post. A short, wide, overly tapered post combined with an artificial crown lacking an adequate ferrule is more likely to fail regardless of cement. If a post is fabricated consistent with sound biomechanical principles, following guidelines in a standard prosthodontic text, conventional cements such as zinc phosphate cement are satisfactory.

DIRECT CORES

Core materials

The three basic direct core materials are silver amalgam, composite, and glass ionomer–based core materials. There have been numerous in vitro experiments that have investigated the physical properties of these core materials. Some studies have been conducted with crowns cemented over cores to more appropriately mimic clinical conditions, and others have loaded the core materials directly to determine their strengths. Conclusions often differ depending on the design of the study, and factors such as applied loading angle have been shown to substantially alter the results.[153]

Properties that are important predictors of the clinical behavior of a core material include compressive, shear and tensile strengths, along with rigidity.[154,155] Silver amalgam has been reported to perform best as a core material under simulated clinical conditions because of its high compressive strength and rigidity.[11,156] Conversely, a number of studies have indicated that materials derived from glass ionomer cement perform poorly as a load-bearing core material.[155-160] Composite has a strength intermediate between silver amalgam and glass ionomer core material and is more flexible than silver amalgam.[11] It appears that composite is an acceptable direct core material when substantial coronal tooth structure remains,[155,157-161] but less desirable when there is limited supporting dentin.[11] Composite is also difficult to condense adequately in the tooth preparation, and a syringe technique has been reported to produce a denser core compared with a bulk-insertion technique.[162]

Several composite core materials contain a fluorosilicate inorganic filler similar to the aluminum fluorosilicate glass in glass ionomer cements. Consequently, these composites release trace amounts of fluoride that may continue for up to 5 years.[163,164] Nevertheless, as with the fluoride leached from glass ionomer cements, clinically relevant cariostatic properties have not been established with these fluoride-containing composite core materials.

Bonded cores

Contemporary adhesive dentistry allows for the bonding of cores to the remaining tooth structure.[16,17,165-167] Bonding techniques will augment the mechanical retention of a core, but should not be used as the sole means of retention.[18,165,168] The high fracture strength of silver amalgam can be improved in vitro with the use of an amalgam bonding agent, although the clinical relevance of the effect of the bonding procedure after prolonged intraoral function are unknown.[17] Amalgam bonding techniques result in an adhesive resin at the interface between the tooth and the silver amalgam, and marginal leakage has been reported after in vitro aging for 30 days.[169] However, leakage at the core margin should not be a problem when amalgam bonding agents are used because the margins of the artificial crown completely cover the core / tooth interface.

FOUNDATION RESTORATIONS FOR SEVERELY COMPROMISED TEETH

In the past pulpless molars were resected and restored with complex restorative techniques as a method to retain compromised teeth and avoid the need for removable prosthetic restorations.[170] These restorative procedures are technically demanding and expensive. A failure rate ranging from 32% to 38% within the first 10 years of service has been reported for resected molars,[171,172] although teeth that survived 10 years appeared to have a better long-term prognosis.[173] Construction of a foundation restoration to retain a complete crown is especially difficult with a resected tooth, and a relatively high percentage of failures appeared to be the result of restorative failures and faulty resective procedures.[174]

With the advent of predictable osseointegrated implants to support and retain prosthetic restorations,[175-179] the practice of retaining severely compromised teeth has diminished substantially. Often it is in the best interest of the patient to extract teeth with a poor prognosis and replace the compromised teeth with implant-supported artificial crowns or FPDs.

CURRENT PROBLEMS AND LIMITATIONS

Despite the large volume of published research on foundation restorations, major gaps exist in the profession's current knowledge on this topic. There are numerous in vitro studies of different approaches to foundation restorations, primarily involving methods of restoring pulpless teeth; but data from these in vitro investigations are frequently conflicting and not always applicable clinically.[31] Several retrospective clinical studies of restored pulpless teeth have been reported in the literature.[28,37,180-185] Nevertheless, the results of these studies are also conflicting, and it is difficult to formulate meaningful clinical guidelines based on diametrically opposed results.

With any retrospective study, there are problems with control of the treatment methods, and the procedures provided are commonly biased. For example, it can be assumed that the dentists who provided treatment for the patients surveyed in a retrospective study used clinical judgment to select the method of treatment. Teeth with minimal remaining coronal dentin may have been restored with custom cast posts and cores, and those with substantial residual tooth structure may have received prefabricated posts or foundation restorations without posts. Consequently, with this hypothetical treatment protocol, the teeth restored with cast posts would be at a higher risk of failure not because of any inherent problems with the procedure but because the dentists selected cast posts and cores for teeth with the least supporting dentin and the poorest prognosis.

FUTURE NEEDS

With the advent of new materials and techniques, additional in vitro and in vivo studies are required to fully evaluate the efficacy of these recent developments. The carbon-fiber reinforced epoxy resin post and zirconia post, as well as recently introduced cements and bonding techniques, are among these new materials and procedures. Currently, there is sparse scientific knowledge relative to the long-term prognosis of teeth restored with these approaches.

Further improvements in direct core materials would also be welcome. Silver amalgam is the most mechanically sound core material, but health concerns about its mercury content continue.[186] A silver amalgam core is eventually totally covered with a complete artificial crown and not exposed to the oral environment; thus, a silver amalgam core is unlikely to contribute any systemic mercury to the patient. Nevertheless, the day may come when silver amalgam is not available in dentistry for any purposes, and a suitable substitute for direct cores will be necessary. Composite core materials can provide favorable mechanical results when there is adequate remaining supportive dentin, but the flexibility of current formulations limit their use when extensive coronal tooth structure is missing. Reinforcement with silanized glass fibers or polymer-impregnated fibers has been suggested as a method of improving the flexural strength of dental resins. This approach may improve the physical properties of resin-based core materials.[187] In addition, health related issues may also arise with composites. Organic constituents have been reported to leach from dental composite resins, and the biologic effects of these eluded organic materials are unknown.[188-191]

SUGGESTED DIRECTIONS FOR FUTURE RESEARCH

Randomized controlled clinical trials would provide the most reliable data on the prognosis of teeth restored with foundation restorations, but these studies are prohibitive, and data relative to long-term success rates would be unavailable for many years. Retrospective clinical studies are more cost-effective, and if well executed, can serve as reasonable alternatives to randomized controlled clinical trials. The dental profession needs more high-quality retrospective clinical studies on this topic, and investigations of patients treated in a relatively controlled environment such as a dental school would likely provide more valid results than those reported from the currently available retrospective investigations. For maximal reliability and validity, retrospective data should be collected from large groups of patients, with records chosen randomly by chance from a pool of patients who received treatment that is consistent with recommended procedures found in standard texts.

SUMMARY

The topic of foundation restorations involves many materials and techniques used daily in dental practice. This comprehensive article reviewed literature from various in vitro and in vivo investigations in addition to technical and clinical reports to provide meaningful guidelines for selection of methods and materials for restoration of structurally compromised teeth. Limitations in current knowledge of this topic and directions for future research were also suggested.

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