Root Fortification

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Abstract

An incompletely formed tooth is left with thin dentin walls and experiences a higher incidence of cervical root fracture that reduces the long-term overall prognosis of the tooth. Faced with these situations, clinicians have attempted to use various restorative methods to reinforce the remaining root. Various techniques have been reported, and the scientific evidence for each has been reviewed. The biomechanical considerations of reinforcing a weakened root are also reviewed, and the most current information about failure analysis, fracture characteristics of natural dentin, and in vitro test configurations used have been considered. In light of these additional considerations, some recommendations for future understanding of this complex problem have been proposed. (J Endod 2013;39:S57–S62)

Key Words

Failure analysis, fracture fatigue, immature roots, root fortification, root reinforcement

Every practicing dentist observes and encounters fractured teeth daily. A patient survey of more than 14,000 molars by the Practice-based Research in Oral Health network from the Oregon Health and Science University revealed the virtually ubiquitous presence of cracks in these teeth (1). In the adult population a vast majority of cracks are found in posterior teeth and are most prevalent in mandibular molars, with the highest prevalence rates in patients older than 40 years (2–5). Although the presence of cracks in these teeth is almost universal, complete tooth fracture incidence has been reported at 5 fractured teeth per 100 adults per year, with a vast majority of those being posterior teeth (6). It has been shown that 44% of crowns performed by a group of general dentists in North Carolina were done to prevent tooth fracture (7). This same study also showed that when different dentists examined the same patients, there was little consensus about which teeth should be crowned to decrease the risk of future fracture. Understanding how teeth fracture and which fractures require fortification to preserve the remaining tooth structure remains controversial.

In the young adolescent population the risk of fracture is more common in anterior teeth and is a result of acute dental trauma (8). Prevalence estimates suggest that up to one-half of children ages 5–18 will incur some type of dental injury during their school years, and the majority of dental trauma occurred before the age of 12 (86%) (9). The most common injuries to permanent teeth occur as a result of falls, followed by traffic accidents, violence, and sports (10–14). For participation in high-risk sports, the American Academy of Pediatric Dentistry encourages the use of protective gear, including mouth guards, that help distribute forces of impact, thereby reducing the risk of severe injury (15, 16). Trauma leading to complicated crown fractures and/or pulp necrosis can be a significant problem in this population because of incomplete root development commonly found in these teeth. Incompletely formed teeth with thin dentin walls have been shown to experience higher incidences of cervical root fracture, which lead to reduced long-term overall prognosis (17, 18). The frequency of fracture is markedly higher in immature incisors than in mature incisors, and the frequency is dependent on the stage of root development and, therefore, the amount of dentin thickness (19).

Consequently, faced with these clinical situations and the evidence that the fracture rate of these teeth can be very high, clinicians have attempted to use various restorative methods to reinforce such weakened teeth and have reported these techniques and their observations in case reports (20–23). In the absence of our profession’s ability to run controlled clinical trials to answer many of our important questions, much research is done in the laboratory setting under controlled conditions. There are numerous in vitro studies in which bovine, sheep, or human teeth with enlarged canals have been used to simulate immature teeth. In this review we attempt to summarize those laboratory findings, introduce some of the biomechanical considerations that need to be critically examined, and draw some conclusions on how best to proceed with the examination of long-term clinical optimization of root fortification.

Techniques and Materials Used for Root Reinforcement

Replacing Missing Tooth Structure with Natural Dentin

Several case reports have discussed methods for pulp space revascularization and apical tissue regeneration to continue root development and produce root-end closure (24, 25). An excellent review of this area has been presented by Trope (26) and is not part of this discussion. However, the replacement of missing tissue with artificial means cannot possibly compete with the biological replacement of the missing tissue with natural dentin. This area of research should continue to have a high priority for support because of the potential that has already been demonstrated. This will eliminate the need

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to create durable interfaces between the artificial materials and natural dentin, which remains a challenge. However, until such a time when these techniques become predictable and mainstream, there will be interest in alternative methods of root fortification.

**Mineral Trioxide Aggregate**

Calcium hydroxide (Ca(OH)₂) has been used for various endodontic procedures including interappointment antibacterial dressing, pulp capping, pulpotomy, and apexification (27–29). It has been a common practice to use long-term Ca(OH)₂ dressings to promote formation of a hard apical barrier at the open apex of immature teeth to allow condensation of a gutta-percha root filling (30). In addition, previous studies have shown that Ca(OH)₂, on prolonged contact with dentin, adversely affects the root strength and fracture resistance (31–34). Recent studies suggest using mineral trioxide aggregate (MTA) as an apical plug, which reduces the duration of the Ca(OH)₂ dressing and overall treatment time (35–37). Apatification of these underdeveloped teeth with Ca(OH)₂, and more recently with MTA, has led to successful resolution of the periapical lesion, but neither method can lead to further dentin development and thus leaves the tooth in a weakened state.

Consequently, MTA materials have largely replaced Ca(OH)₂ as endodontic repair materials. It has been demonstrated that MTA stimulates reparative dentin formation, with thick dentinal bridging, minimal inflammation, and nominal hyperemia. The net result is that vital pulp therapy with MTA produces negligible pulpal necrosis (35–42). MTA is a calcium silicate–based material with chemical similarities to ordinary Portland cement. It has been modified with reduced heavy metal content, increased radiopacity, better particle distribution and size, lower solubility, and reduced setting expansion to meet the demands of a biomaterial (43). MTA is classified as a hydraulic cement that sets and is stable under water. Because of components similar to those of Portland cement, it may be assumed that MTA sets through a hydration reaction that involves dissolution of calcium silicate granules to produce Ca(OH)₂ and calcium silicate hydrates, which form the matrix that holds hydrated granules and contains water-filled micropores where the Ca(OH)₂ distributes (44).

The release of Ca(OH)₂ provides the high alkalinity and is believed to be responsible for its ability to induce hard tissue formation when used as a pulp-capping material.

Because of the relatively poor strength properties of MTA (45, 46) and an earlier study that suggested that prolonged contact of root dentin with Ca(OH)₂ or MTA resulted in similarly severe reductions (32% versus 33%) in dentin fracture resistance (33), several modifications to the original composition have been made (47,48). More recent in vitro investigations showed that MTA-filled roots had significantly greater fracture strength than CaOH₂-filled roots but no different than unfilled roots after saline storage for 100 days (49). Similar results were reported for MTA and a modified MTA (DiaRoot; DiaDent Group International, Burnaby, BC, Canada) with respect to CaOH₂-filled roots (50). There appears to be some consensus that MTA does not weaken the dentin to the same extent as CaOH₂, although some negative effect on dentin strength has been demonstrated by Sawyer et al (51) after 2–3 months of contact. The ability for MTA to reinforce weakened teeth is still open to some debate. One investigator found that the fracture strength of MTA was greater than gutta-percha filled and not filled canals after 48 hours (52). Another investigator showed that the reinforcing effect could not be detected until after 1 year of storage when compared with the unfilled control (53). Yet another investigator found that after thermocycling, MTA did not improve the fracture resistance of weakened roots when compared with an unfilled control (54). It would appear from the current data that the strengthening effect of MTA cement alone as a root fortification material is minimal at best but may not negatively impact the dentin properties to the same extent as CaOH₂.

**Glass Ionomer Cements**

The use of glass ionomer cements (GICs) in both conventional and surgical endodontics has been reviewed by De Bruyne and De Moor (55). GICs, like MTA, are also water-based restorative materials. However, unlike MTA, GIC setting involves an acid-base reaction that generates the formation of polyalkenoate salts as a result of the acid attack on fluoroaluminosilicate glass fillers. Because they are of an acidic nature, GICs are considered self-etching cements, and on wet dentin, they trigger an ionic exchange with the interface, accompanied by water movement between the 2 substrates (56). Glass ionomers and resin-modified glass ionomers, with their ability to provide an excellent seal through their chemical interaction and release fluoride for long periods of time, appear to have desirable properties for root canal sealing. However, with respect to MTA they do not offer any demonstrable dentinogenesis characteristics (55).

The information available on the use of glass ionomer or resin-modified glass ionomers as an endodontic filler to reinforce the remaining root appears to be limited. At least 1 case report with a 2-year follow-up has demonstrated a successful outcome (57). At least 3 laboratory studies were found that examined the root-reinforcing ability of GICs. Only 1 investigation using the immature tooth model could be found. In this study the glass ionomer–restored root had significantly higher fracture resistance than the unrestored root (58). Atmeh et al (44) showed that the interface between the dentin and the GIC was a tight junction but did not have the same extensions into the tubules as did the MTA. Similar to adhesive resin technology, it is not clear as to the extent to which these macro retentive features contribute to interface attachment and its durability over time.

**Composite Resin**

As early as 1985, composite was shown in a laboratory study to increase the resistance to fracture of endodontically treated teeth (59). Since that time, both flowable and hybrid composites have been shown in the laboratory to have this ability to reinforce simulated immature roots (60–65). In experiments specifically with simulated weakened roots, Schmoldt et al (54) found no significant difference in the reinforcement of roots restored with composite resin compared with the gutta-percha–filled canals after thermocycling. The stability of the bond between the restorative material and the dentin interface over time and under service conditions is an important aspect of long-term root fortification that has been largely ignored in laboratory testing, and it is currently unclear to what extent these considerations may alter the outcome.

**Using Posts to Reinforce Roots**

The question of whether posts reinforce teeth is one that has been examined extensively and is perhaps the most complex and confusing issue that faces our profession today. There is some consensus that posts do not strengthen the roots of teeth (64–66). However, in a recent national survey of German dentists, more than 50% of those who responded believed that posts reinforce endodontically treated teeth (67). The American Association of Endodontics has recommended that posts only be used to retain core buildups (68). However, their perspective is one of protecting the apical seal first and foremost.

The ability of various posts to reinforce weakened roots has been examined by numerous investigators who used the immature root
laboratory model. One such study has demonstrated that weakened teeth restored with a resin retained cast post and core required significantly less force to fracture than those restored with various bonding techniques (69). By using a similar weakened-tooth model, another group has demonstrated that reinforcing the tooth with a bonded thin zirconia post was no better than just filling the enlarged canal with composite (70). However, both scenarios were the same as for a tooth whose canal was not enlarged or weakened (negative control). In another study it was suggested that a composite core alone would eventually fail from fracture propagation of defects in the bulk material and suggested that a fiber composite laminate could be used to reinforce weakened teeth. In this study a polymer fiber (Ribbond, Seattle, WA) was used to reinforce composite cores but actually resulted in lower loads to failure than composite alone (63). By using this same weakened-tooth model, it was found that fiber post and composite resulted in significantly higher failure loads than the normal size canal with no restoration (negative control), but the use of composite alone to restore the enlarged canal was still significantly higher than the enlarged canal with MTA or gutta-percha alone (54). This group thermocycled their specimens before testing to simulate some form of stress at the bonded interfaces, because the durability of the bond will ultimately determine the long-term success of such an effect. Manicardi et al (71) used push-out bond strength of adhesively bonded fiber posts and found that bond strengths were not affected by the root canal sealer or location in the canal. The fracture resistance of teeth reinforced with fiber post has been examined by several investigators, and the results have been mixed. In 1 study it was found that thin-walled roots reinforced with fiber posts were significantly stronger than unrestored roots but no stronger than gutta-percha sealed with an epoxy resin (AH Plus; Dentsply DeFrey GmbH, Konstanz, Germany) (72). Other studies have found both glass fiber reinforced and thermoplastic (Resilon; Pentron Clinical Technologies, Wallingford, CT) reinforced thin-walled roots to be as strong as the unfilled, normal-wall canals (negative controls) (73, 74).

Other groups have investigated the idea of having a thick intermediate layer between the post and the dentin interface. One group has found that a thick intermediate composite layer between the root wall and a thin metal post could significantly increase the fracture resistance of weakened roots compared with a custom cast metal post bonded to the enlarged canal (75,76). The idea of the thick intermediate layer was examined again by Ayad et al (77). Those results indicated the post type (titanium versus fiber post) did not influence the fracture resistance, but composite was significantly more effective as the intermediate layer than resin-modified GIC. Others have used this same strategy in combination with MTA. Two groups have found that a small metal post surrounded by MTA resulted in significantly greater fracture resistance than teeth with MTA alone (52,75).

The question of which fortification method can best be used to reinforce thin-walled roots remains unclear, because most of these studies are simple load to failure analysis and do not account for long-term chemical or mechanical degradation. However, most researchers and clinicians believe that adhesive techniques hold the greatest promise.

Biomechanical Considerations for Root Fortification

Failure Analysis

The field of failure analysis is one that is of critical importance to improving the performance of the object that we are interested in with respect to the forces that it will encounter under normal or abnormal service conditions. Many of the world’s most important industries, including automobile and aviation, use failure analysis to improve performance and guard against catastrophic failures. Crash tests are an example of failure analysis.

Dr. J. O. Andreasen (78) is credited with being the first to classify traumatic injuries of the anterior teeth. In engineering terms this would be classified as failure analysis. These classifications of the observed failures have been put into 2 broad classifications related to fractures of the teeth (enamel infraction, uncomplicated crown fracture, complicated crown fracture, crown/root fracture, and root fractures) and classifications related to the bodily movement of the tooth within or out of the surrounding alveolus (conclusion, subluxation, extrusive luxation, lateral luxation, intrusive luxation, and avulsion) (78).

The types of acute traumatic injuries that occur are related to the direction and magnitude of the acute forces that are applied. In brittle structures such as glass, fractures can occur from surface contact stresses that radiate inward from the point of contact. Teeth can be considered brittle structures (79). Under acute traumatic injuries in which a hard object contacts the tooth surface either directly or indirectly after penetrating the soft tissue, it is likely that the crack initiations that lead to the fracture originate from the surface and radiate inward and through the tooth. Surface-initiated cracks of this nature can only be minimized by diffusing the force of the contacting object over a larger surface area, thus reducing the stress felt by the tooth surface. This would be analogous to the airbag effect in an automobile accident. High energy absorbing elastic mouth guard materials have been developed to protect the teeth and surrounding support structures from damage, and there is evidence that orofacial sports injuries are 1.6–1.9 times higher when a mouth guard is not worn (80).

Root fortification methods should not be considered as a means of reducing the risk of fracture from acute trauma but rather a method to reduce the probability of fractures from normal service conditions. To better understand and model whether a clinical treatment can have an effect on a clinical outcome, such as failure from fracture, it is essential that we understand how cracks propagate through enamel and dentin.

Fatigue and Fracture Properties of Enamel and Dentin

Enamel is particularly weak and can fracture quite easily when a tooth is strained or deformed under even normal chewing forces. This is why older teeth exhibit enamel fracture lines almost ubiquitously. Excessive chewing forces can cause microstrain in the surface enamel that can lead to cleavage fractures between the prisms of the enamel rods. The dentino-enamel junction (DEJ) is known for its unique biomechanical properties that provide a crack-arrest barrier for flaws formed in the brittle enamel and has a hierarchical microstructure with a three-dimensional scalloped appearance along the interface (81). This anatomically thin region represents a functionally graded zone where the enamel and dentin close to the interface have slightly different microstructures and properties than the more distant bulk phases. The region has been shown to successfully transfer applied loads (for example, masticatory or impact) from the enamel to the dentin and can inhibit cracks in enamel from propagating into the dentin and causing catastrophic fracture of the tooth (82). Recently, by using interfacial fracture mechanics, new estimate of the DEJ toughness is 5–10 times higher than enamel but about 75% lower than the dentin itself. Cracks tend to penetrate the (optical) DEJ and arrest when they enter the tougher mantle dentin adjacent to the interface because of the development of crack-tip shielding from uncracked ligament bridging (83,84). It is of particular interest to know that the DEJ is effective at slowing cracks from the enamel surface inward but has little effect on cracks growing from the internal dentin outward, as we see in restored teeth radiating from internal cavity preparation line angles.
For cracks that are already into the dentin, it is of interest to understand how these cracks propagate through the dentin.

It has been commonly thought by clinicians and stated in textbooks that endodontically treated teeth become more brittle. Previous investigations have not been able to demonstrate that the loss of tooth vitality is accompanied by significant changes in dentin properties (85–88). This issue has most recently been addressed by a team of researchers at Lawrence Livermore National Laboratory in California. By using the same fracture techniques that are used to study brittle ceramic materials, researchers have gained a better understanding of how dentin fractures. More current investigations have shown that older dentin responds differently to fracture and fatigue than young dentin. Of greatest significance is that dentin becomes brittle with age. Young dentin can visibly yield and deform before breaking, whereas old dentin does not (89–91). At a microscopic level, older teeth appear to form far fewer microcracks in front of a crack. As a result, less of the strain energy is relieved, and virtually no bridges are produced. The fracture toughness in aged dentin measured about 20% lower than in young dentin (89–91).

This same research group has also answered a long-standing fundamental question in dentin research—how do cracks in dentin propagate? Their research proved that cracks in dentin only grow if the load is cycled, a process known as fatigue. When dentin is held at constant stress, cracks become blunted, increasing the required stress for the crack to advance. Cycling the load permits the crack tip to alternately sharpen and blunt, which advances the crack (89–91). This suggests that to study crack propagation in teeth, we may need to consider alternative laboratory simulation methods.

**In Vitro Test Methods**

To date, a vast majority of studies done on the immature-root model have been done under static or single cycle load to failure testing conditions. These conditions may or may not represent the mode of failure that occurs in service. It is possible that the high incidence of cervical root fractures reported with immature roots (17, 18) is a result of fatigue crack growth over time and not a second incident of acute trauma. In this case it would be more important to understand how the reinforced tooth with an initial crack responds to cyclic stress under normal loading conditions rather than single cycle load to failure test. Fractographic analysis of the fractured surface of failed roots could provide some valuable information related to the origin of the fracture and the direction that it travels (92).

Although this review focused only on those studies that used thin-walled roots to simulate an immature-tooth model, the loading indenter shape and angulation of loading, as well as the coronal portion of the tooth, often varied from one study to another. These variations can lead to different stress concentrations and different ranges of failure loads that were usually well above those that would be encountered under normal conditions other than perhaps acute trauma. In many cases the loading conditions and type of restorative technique being compared lead to comparisons that may not be appropriate, because the modes of failure are different. An example of such a situation is seen in post and core literature. Clinicians and researchers that advocate for adhesive retained fiber posts over cast post and cores because of either longevity or elimination of root fractures can find laboratory studies that might support those claims, but the clinical data are just not there to make those claims. In fact, long-term clinical trials that have looked at failure modes have reported the root fractures from cast post and cores (4%) were similar to root fractures that occurred in teeth with no post (5%). However, the root fractures from prefabricated titanium posts (8%) were greater than both (93). In another 17-year survival study, 36 of 307 post and cores failed irreversibly. Of those failures, only 7 failed from root fractures. Of the post types, 2% of the cast metal post and cores and metal post with composite cores failed from root fractures after crown coverage, whereas about 7% of the teeth without posts failed from root fractures (94). The overall failure rate from fractures appears to be very low (95–98), and making conclusions about one system resulting in less root fractures than another may be premature.

**Summary, Conclusions, and Recommendations**

Managing the adolescent patient who has experienced an acute traumatic dental event presents the dentist with significant immediate and long-term challenges. Teeth are surprisingly durable structures that can withstand significant trauma. The type of damage that is incurred by the teeth depends on the magnitude, distribution, and speed with which the force is applied.

Teeth that survive one traumatic incident can be left in a significantly weakened state, and there are no diagnostic tools that can tell us the existence and extent of any residual fractures that may have occurred during the initial trauma. Internal root fortification is not enough to prevent fracture if the tooth is retraumatized with an acute accident. Prevention and mouth guard protection are the most practical solutions. However, in light of what we now understand about crack propagation in dentin, it does make sense to stiffen the root with a restorative method that is durable in an attempt to minimize cyclic strains that can occur in the tooth under normal function. To assess the effectiveness of the various techniques that have been proposed and in the absence of the ability to run randomized controlled studies, there is a need for laboratory tests that can better predict clinical performance.

It would appear that if root fractures are the failure that we are trying to prevent, there is a need to understand clinically how the fractures originate and progress. Fractographic analysis of the surface of failed teeth would need to be the first step. If roots fail from crack propagation of flaws that are left from the original trauma and grow under function, a laboratory model that includes the presence of an existing flaw and cyclic loading would be indicated. If a majority of these roots fail from a second traumatic event, prevention is the only real possibility for long-term survival of the root.

Regardless of the confusion that still exists in the literature, adhesive procedures hold the best promise for root fortification. A combination of a better understanding of the fracture process that occurs and improved laboratory and computer simulations to model the process can help designers predict the most appropriate long-term reinforcement method.

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