

The endodontic management of traumatized permanent anterior teeth: a review

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Abstract

Despite the many journal articles and reviews that have been published regarding the treatment of trauma to teeth, the endodontic management of these injuries is often still not fully understood. The purpose of this review is to establish clear and up-to-date guidelines for practitioners who are faced with treating dental injuries on a day-to-day basis, based on an assessment of current available scientific information relating to the endodontic management of these injuries.

Treatment is discussed under the headings: infractions, uncomplicated crown fractures, complicated crown fractures, crown-root fractures, root fractures, luxation injuries, avulsion, root resorption, pulp canal obliteration and open-apex teeth. Emphasis is placed on the treatment of traumatized immature teeth where maintenance of pulp blood supply is important to encourage continued development of the root system. Only the treatment of traumatized permanent anterior teeth is reviewed.

Information contained in this article is based on a review of the literature on dental trauma which involved a MEDLINE search using the key words "dental trauma" and the individual topics listed above. The guidelines produced by the International Association of Dental Traumatology, the American Academy of Pediatric Dentistry and the American Association of Endodontists were also reviewed and the recommendations contained in this paper are in concert with the major recommendations of these bodies.

Key words: Dental trauma, review.

Abbreviation: MTA = mineral trioxide aggregate.

INTRODUCTION

The management of patients who have suffered traumatic injuries to their dentition is an integral part of general dental practice. This will continue to be the case given the ever-increasing incidence of dental trauma as a result of traffic accidents, sporting injuries, risk-taking physical activities, violence and child physical abuse in modern society.¹⁻³ There are already

numerous texts and articles which discuss the causes and incidence of dental trauma.⁴⁻⁸ It is not the purpose of this review to consider these aspects of dental trauma; instead, the immediate and long-term endodontic management of traumatized teeth is the focus of this review. It would be remiss not to state, however, that all clinicians must be cognizant of the fact that some dental injuries to children may be a result of child abuse, and there is a need to be vigilant in assessing an injured child and the circumstances of an injury to distinguish, where possible, between accidental injuries and injuries from abuse.¹⁻³

Dental injuries often involve damage not only to the tooth, but also to the supporting tissues. If treatment is to be completely successful, an examination of a patient with dental injuries must pay attention to both components jointly. Soft tissue injuries should be assessed; displaced or lacerated tissues should be immediately repositioned and where necessary sutured into place.⁴ Where soft tissue injuries occur concomitantly with tooth fractures, the soft tissues should be examined for the presence of embedded tooth fragments.

A number of studies have confirmed that fracture of the tooth results in disruption of the energy of the blow and minimizes damage to the periapical region.⁹ Tooth mobility is more often associated with teeth without hard tissue damage than with teeth that are fractured.⁹ Prognosis is better in teeth with hard tissue damage than in teeth that are luxated.^{4,10} Where the supporting tissues are concurrently damaged, the prognosis for the tooth, particularly with respect to the vitality of the pulp, is poorer.¹¹ Thus, teeth that are not obviously traumatized may be the ones that could present long-term management problems.

No review on the management of dental traumatic injuries would be complete without a discussion of the need to fully assess a patient with dental injuries: assessing the injured dental hard and soft tissues, injuries to supporting tissues and to the patient as a whole. The systematic assessment of a patient with traumatic dental injuries is well covered in the literature.^{4,8,12} Many strategies have been suggested for the prevention of traumatic dental injury and there is considerable evidence to support the efficacy of these preventive aspects pertaining to dental injuries.^{4,12,13}

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Splinting of teeth with luxation injuries, avulsions and root fractures is often necessary to stabilize a tooth in position, and to assist in periodontal and pulpal healing. A flexible splint has been shown to be the most desirable.^{4,14-16} The American Academy of Pediatric Dentistry suggests that an ideal splint should amongst other things: be easily fabricated in the mouth without additional trauma; be passive, unless orthodontic forces are intended; allow physiological mobility; be non-irritating to soft tissues; not interfere with the occlusion; allow endodontic access; be easily cleaned and easily removed.¹⁷ Recommended splinting times are up to two weeks for most avulsion and luxation injuries unless they occur in association with alveolar fractures, up to four weeks for lateral luxation injuries, alveolar fractures and root fractures, and up to four months for cervical-third root fractures.¹⁸ Many dental injuries do not occur singly. Thus, these splinting times cannot be rigorously applied. In general, splinting times have to be adjusted to accommodate the more major injuries.

All traumatic dental injuries need to be followed up over time. Follow-up procedures include a clinical examination, a radiographic assessment and pulp sensibility testing. Recommendations for follow-up examinations for injuries proposed in this study are in accord with those recommended by the International Association of Dental Traumatology.¹⁸

While continued negative responses to pulp testing procedures imply that a pulp has become necrotic, pulp sensibility testing procedures test only a neural response. Blood vessels and nerves differ in their elasticity. Thus, it is possible to disrupt the nerve supply to a tooth without disrupting blood supply. Also, it is possible for a pulp to revascularize without there being a concomitant neural regeneration. Hence, the absence of a positive result to pulp sensibility testing does not automatically imply loss of vitality of pulpal tissues. Careful attention must be placed on clinical assessment and an examination of changes that occur both within the pulp canal and at the apex. If calcification continues to occur, the pulp must be regarded as vital even if the response to pulp sensibility testing is negative or ambiguous.

Recommendations for the overall management of dental trauma have been produced by the International Association of Dental Traumatology and the American Academy of Pediatric Dentistry,¹⁷ and in a number of texts^{2,4,8,12} and articles.¹⁹⁻²³ This paper specifically reviews only the endodontic management of traumatized permanent anterior teeth. The role of endodontic treatment following trauma to these teeth has been reviewed in the past.²⁴⁻²⁷ In this study, the endodontic management of teeth that have been traumatized is discussed in light of recent developments and guidelines for their endodontic management are described. In the past, variations in classification techniques, clinical assessment procedures, observation times, and shortcomings in the statistical assessment of data have all clouded the issue. More recently, however, thanks to

the rigid methodology proposed by Andreasen and his many co-workers,⁴ many of these variations have been eliminated from the literature. The classification of dental injuries described by Andreasen⁴ is, in general, followed.

Infraction

Infraction injuries involve damage or cracking of the enamel without any loss of tooth structure. Only a few studies have investigated pulpal complications following this type of injury. Pulpal complications are considered to be rare (0–3.5 per cent) unless there is an associated luxation injury.^{4,28,29} Pulp treatment should only be carried out in the presence of signs and symptoms of irreversible pulpitis or pulp necrosis with infection. In assessing pulpal damage, clinicians must remain cognizant of the fact that reactions to pulp sensibility testing in traumatized teeth are lowered immediately following trauma and longer observation times (up to at least eight weeks initially) may be required before a definitive decision can be made regarding the state of the pulp.^{30,31} As with all traumatic injuries, further follow-up after 12 months is advised.

Uncomplicated crown fractures

In uncomplicated crown fractures there is loss of tooth structure without an exposure of the pulp. These injuries can involve the loss of enamel only or loss of enamel and dentine. Pulpal complications rarely occur in teeth with enamel fractures only (0–1 per cent),^{29,32,33} unless there is an associated luxation injury (8.5 per cent).³² In the absence of concomitant luxation injury, complications resulting from injuries involving both the enamel and the dentine are also infrequent (0–6 per cent).^{10,34,35} An increased incidence of pulpal necrosis in teeth with combined fracture and luxation injuries has been clearly established (25 per cent).^{10,34} In the absence of simultaneous luxation injuries, complications are also believed to develop from bacterial penetration into open dentinal tubules. Dentine coverage is indicated for all these fractured teeth. Relevant determinants of prognosis are: the type and site of fracture; the presence of luxation injury; the type of treatment undertaken and the timing of treatment. Pulp necrosis occurs more often in deep angular fractures and in deep fractures that are left untreated for more than 24 hours. Lost tooth structure can be restored by restorative materials^{4,23,36} or by re-attachment of the fragment.^{4,23,37-39}

The prognosis for re-attached crown fragments is good and continues to improve with the increasing bond strengths achievable with dentine bonding agents.⁴⁰ Thus, patients should be advised to search for and bring any tooth fragments with them when presenting for treatment. Reinforcing the fragment margins with composite resin does not appear to have any significant effect on the retention rate of the fragment.⁴⁰ Placement of an internal groove within the dentine of the fragment to improve retention by increasing the surface area available for bonding has

been suggested.³⁷ Composite restoration with fibre reinforcement has a higher load-bearing capacity than conventional composite restoration.⁴¹ Porcelain laminate veneers are a predictable, effective and relatively conservative way of reinforcing the strength of a re-attached fragment.^{42,43}

Follow-up and treatment of uncomplicated crown fractures

Endodontic treatment of teeth with uncomplicated crown fractures is usually unnecessary unless pulp necrosis and infection develop subsequent to the injury. With minor injuries, treatment can be restricted to smoothing of rough edges and review. As prognosis is related to time before treatment, dentine-covering procedures should be urgently instituted as soon as possible for fractures involving the dentine, particularly for deep and angular fractures, and when there has been an associated luxation injury. This typically involves re-attachment of the fractured segment or restoration of lost tooth structure with composite resin.

As reactions to pulp sensibility testing procedures are often lowered immediately after injury, sensibility testing of teeth with uncomplicated crown fractures can, in general, be delayed for a short time after injury, particularly in the presence of haemorrhage and associated soft tissue injuries, or where sensitivity to thermal stimulation or to touching the exposed surface clearly indicates that the pulp is responsive. Reversal of negative sensibility testing results can occur, particularly in immature teeth and in teeth with open apices. If pulp problems are to arise, they will generally occur within the first six months after injury. In view of the fact that the pulps in traumatized teeth can become necrotic and infected even a number of years subsequent to injury, routine sensibility testing at six to eight weeks and then at yearly intervals should be included in the treatment regime.¹⁸ Sensibility testing and assessment of adjacent teeth should also be routinely undertaken at regular intervals.

Complicated crown fractures

Complicated crown fractures are those in which fracture of the crown involves the pulp. Where exposure of the pulp occurs, some urgent form of treatment is necessary if the health of the pulp is to be maintained. Except in immature teeth,^{44,45} most traumatically exposed pulps in anterior teeth will become necrotic and infected if left untreated for one month.⁴⁶ A number of procedures have been recommended for the treatment of exposed pulps. These include pulp capping, partial pulpotomy, pulpotomy and pulpectomy procedures.

In the absence of luxation injury, necrosis of an exposed pulp does not usually occur immediately, although this is the inevitable response if an exposed pulp is left untreated. Inflammatory responses and bacterial contamination, which are responsible for necrosis in exposed pulps, are confined to the site of the

exposure for some time.^{47,48} Accordingly, in traumatically exposed teeth, both pulp capping procedures and partial pulpotomy procedures have been shown to be successful, particularly in younger patients. Pulpotomy procedures appear to be superior to pulp capping⁸ and involve removal of the “injured” coronal pulp usually at the level of, or near to, the coronal opening of the root canal and the placing of medicament (usually calcium hydroxide) against the remaining vital tissue. Treatment seems to be more successful if the medicament is placed directly onto the exposed pulp without an intervening layer of haemorrhage.⁴⁸ Cvek has reported that 96 per cent of exposed pulps, which were amputated about 2mm below the exposure site with a high speed diamond bur and then covered with calcium hydroxide after removal of the blood clot, survived and developed calcific bridges at the fracture site.⁴⁸ The success rate did not appear to be related to the size of the exposure, the location of the exposure, or to the time interval between trauma and treatment. Recent studies have confirmed the success of Cvek’s original procedure and suggested the criteria for the use of this technique be expanded to include all traumatically fractured teeth regardless of the patient’s age and degree of apical closure of the teeth, and that the restoration placed at this time could be considered a definitive one rather than a temporary measure.⁴⁹ The advantage of both pulp capping and partial pulpotomy procedures in young teeth, if they prove successful, is that a healthy pulp is maintained throughout the root canal system. This is an especially important consideration in the treatment of young and immature teeth as, in these teeth, measures should be taken to maintain a healthy pulp, not only to ensure apical maturation, but also to promote the development of lateral root dentine to improve root strength. These procedures should only be carried out on vascular pulps. Recently, partial pulpotomy procedures involving the use of mineral trioxide aggregate (MTA) have been described and have been shown to be effective. Proponents of the use of MTA suggest that it helps to protect the pulps from the effects of bacterial penetration and that its use precludes the need to re-enter the exposure site to place a more definitive restorative material over the exposure at later date.⁵⁰

Endodontic treatment of complicated crown fractures

In young patients, the aim of treatment should be to maintain a healthy pulp to permit closure of the root apex and to encourage development of lateral root dentine. Partial pulpotomy or pulp-capping procedures are indicated for complicated crown fractures in these teeth. The partial pulpotomy procedure described by Cvek⁴⁸ (i.e., removal of a portion of the pulp using a “gentle technique” (high speed diamond bur with copious water spray), elimination of the blood clot (by irrigation) and capping with calcium hydroxide or MTA followed by regular recall), has been regarded as

the treatment of choice.⁵⁰⁻⁵² Since resin-based quick-setting calcium hydroxide preparations inhibit polymerization of composite resin materials, their use in these circumstances should probably be avoided.⁵³ Should deep pulpotomy (rather than partial pulpotomy) procedures be necessary due to major crown loss in immature teeth, the problem of calcific bridge formation at the pulpotomy site, which may obstruct pulpectomy procedures at a later date, can be overcome by the use of a corticosteroid/antibiotic combination (e.g., Ledermix® Paste or Endopaste®) rather than a calcium hydroxide material.⁵⁴ As with any conservative pulp therapy procedure, it is important that the medicament is placed directly onto healthy non-inflamed tissue and that the exposure site is protected against bacteria. In older patients, where the success rate for conservative pulp therapy on mature traumatized teeth is less predictable and tooth formation is complete, routine endodontic therapy is more likely the treatment of choice. Nevertheless, since it has been shown that partial pulpotomy procedures can still be successful in older patients, the decision whether or not to retain the pulp is more often governed by the amount of remaining root dentine and the requirements for crown retention rather than whether the pulp is exposed or not. Although the outcome may not be as predictable in the long term, partial pulpotomy procedures can provide an expedient and much cheaper treatment option for some patients, particularly if there is sufficient tooth structure remaining for the crown to be restored with a composite resin material or by re-cementation of the fractured segment.

Crown-root fractures

Crown-root fractures involve the enamel, dentine and part of the root (cementum) surface of the tooth. The fracture line invariably passes subgingivally. The pulp is often exposed and endodontic therapy is generally necessary if the tooth is to be retained. A number of treatment alternatives are available depending on the position and circumferential extent of the fracture, and the severity of the fracture in a subgingival direction. Treatment options were reviewed by Moule and Heithersay⁵⁴ and they include: periodontal surgery to expose crown margins, restorative management only with extension of the margins of the restoration below the level of the gingival margin, orthodontic extrusion, intentional replantation (surgical repositioning), autotransplantation, root submergence (decoronation), extraction and replacement, or orthodontic space closure. Treatment of crown-root fractures can be complex and time consuming. However, most teeth with these types of fractures can be saved.¹⁷ In an adult patient, implant replacement is sometimes a viable alternative. In the case of a growing patient with a tooth that is not restorable, root submergence (decoronation) may be indicated to preserve bone and allow for normal

alveolar development prior to implant placement when growth is complete.^{55,56}

Endodontic treatment of teeth with crown-root fractures

If a decision is made to retain the tooth, either permanently or as a short to medium-term measure until the patient is practically able to have the tooth replaced, endodontic therapy is usually necessary. This can be complicated by difficulties in isolation and the maintenance of a dry field due to the subgingival position of the fracture line. If the crown fragment is lost, isolation for endodontics is best achieved by using a rubber dam cuff supplemented by cotton rolls in the labial sulcus and the use of haemostatic agents, Cavit® or a cyanoacrylate adhesive. A single step endodontic procedure can be carried out as a definitive treatment, or as a temporary measure to be redone at a later date when the situation is more under control. If the fragment is available, it can be re-attached as an interim measure to the remaining tooth structure using a dentine bonding agent and composite resin. Endodontic therapy can then be carried out in the standard manner using rubber dam before proceeding to the next stage in managing the fractured tooth. Failing this, a temporary composite restoration may be placed through which endodontic therapy can be performed.

In the young patient, the procedures may be complicated by lack of root development. The priority in treatment should then be development of root maturity rather than restoration of aesthetics and function. If root development is incomplete, and if the fracture passes deeply subgingivally and involves most of the crown, conservative pulp treatment should be initiated to maintain the health of the radicular pulp while normal root development proceeds. The canal orifice can be temporarily sealed and a temporary denture inserted until further root development occurs. Subsequently, when the root is mature, standard endodontic management can be carried out and routine restoration undertaken. Root submergence (decoronation) is sometimes an option in these cases.⁵⁶ In assessing crown-root fractures in young patients, consideration must also be given to the fact that continued eruption of the tooth may bring a subgingival margin into more favourable position without the need for restorative, orthodontic or surgical intervention.

Root fractures

Root fractures pass across the root and involve the cementum, dentine and the pulp. They can present with or without clinical signs of luxation of the coronal fragment, and they are an indication for routine radiographic examination of all traumatized teeth. The clinical sign is commonly an extruded and lingually displaced crown. The fracture can appear radiographically as a single line or multiple lines across the root.⁵⁷ The image of the fracture is dependent on the

angle of the fracture and the angle at which the film is taken. It is usually clearly evident on radiographic examination, although multiple radiographic views at different vertical angles may be necessary to obtain a clear image. Flores *et al.*²³ suggest occlusal and tube-shift radiographs, in addition to a parallel periapical radiograph, are useful to identify and investigate root-fractured teeth. Radiographs taken immediately following trauma may not show the fracture line clearly.

Many root fractures heal without intervention in one of three modalities: hard tissue interposition, interposition of bone and periodontal ligament or interposition of periodontal ligament alone.⁵⁸ A non-healing inflammatory process associated with pulp necrosis and infection of the coronal fragment can also occur. Factors that have an effect on healing include age, stage of root development, mobility, fragment dislocation and the separation between the fragments. Pulp tissues are not essential to the healing of a root fracture.⁵⁹ Healing is more favourable in incompletely-formed teeth and where displacement of the coronal fragment is minimal.^{58,60} Pulp canal calcification is a common feature that may develop in root-fractured teeth, but this rarely poses a problem in the long term. Canal calcification can only occur if the pulp tissues remain vital.

Pulp survival rates are higher in root-fractured teeth than in traumatized teeth without fracture. Pulp necrosis has been reported to range from 20 per cent to 44 per cent.⁵⁸ In most instances, if pulp necrosis develops, it will do so within two to five months after the trauma. Maintenance of pulp vitality is affected by the extent of apical maturation, the location of the fracture site, the extent of dislocation and the separation between the fragments. If separation is greater than 1mm the incidence of pulpal necrosis in the coronal fragment increases substantially, suggesting that this is the limit to which the pulp tissue can be stretched before first the neural and then the vascular components are compromised.⁵⁸ Should the fracture communicate with the gingival tissues, pulp necrosis inevitably occurs and the prognosis for the coronal fragment is extremely poor.

Pulp sensibility testing immediately after trauma is an unreliable means of predicting the final status of the pulp.⁶¹ Sensibility testing involving thermal and electrical stimuli is nevertheless an important feature of the initial examination of a root-fractured tooth.⁶² A negative response is a common finding immediately and for some time after the root is fractured and is an indication that the pulp has suffered some trauma. Teeth that initially give a negative response can respond after periods ranging from one month to one year. Responses to sensibility testing need to be followed up over time before a diagnosis is made of pulp necrosis. Endodontic treatment is only indicated for those teeth in which pulp necrosis has occurred.⁵⁹ In a root-fractured tooth, this diagnosis is usually based on the development of radiographic changes, often a widening

of the space between the two segments and of the periodontal ligament space adjacent to the fracture site, and the development of tooth discolouration or a sinus tract. Localized root resorption may at times occur in the area of the fracture. This should not be taken as a sign of pulp necrosis without other corroborating evidence.

As the blood supply to the apical fragment is usually not disturbed, if pulp necrosis occurs, it is invariably restricted to the coronal fragment only.⁵⁹ Thus, the endodontic management of root-fractured teeth can be restricted to the coronal fragment. It has been clearly established that the insertion of calcium hydroxide in the root canal to the level of the coronal fracture leads to the production of a barrier at the level of the fracture site, permitting root filling to this level without over extension.⁵⁹ More recently, the use of MTA has been recommended in some cases.^{8,63} Early and accurate repositioning of the coronal fragment has been shown to reduce the likelihood of pulp necrosis.⁶⁴ Optimum repositioning should be verified radiographically.

Traditionally, long-term rigid splints have been used in an attempt to promote hard tissue healing of root-fractured teeth. A recent review,⁶⁴ however, found no real difference between teeth that were splinted in this manner when compared to non-splinted teeth. Where excessive mobility dictates the need for a splint, it should be non-rigid, atraumatically placed and removed after a maximum of four weeks, except in teeth where the fracture occurs in the coronal third where the tooth may need splinting for up to four months.^{18,64} As a general rule, the location of the fracture has not been shown to influence the survival of the pulp; except that in permanent teeth, pulp necrosis is less likely in teeth fractured in the coronal one-third of the root.⁵⁸ The long-term prognosis of these teeth is poorer, however, principally due to an increased susceptibility to new luxation injury or increased mobility of the coronal fragment.^{58,65}

Root fractures are rare in immature teeth as these teeth are more likely to be avulsed or luxated than to be fractured. However, where root fractures occur, the possibility of calcific repair is quite high.⁵⁸ Endodontic treatment is generally unnecessary in root-fractured immature teeth.

Endodontic treatment of root-fractured teeth

The initial treatment of teeth with root fractures is a relatively simple matter provided attention is paid to a few principles. An initial assessment must be made as to whether the fracture line is communicating with the oral cavity, or that it could potentially communicate with it due to tooth movement and gingival recession. Should this be the case, the coronal fragment will generally need to be removed, and the remaining root structure assessed on its merits. If the tooth is to be retained, the tooth should be treated as a deep crown-root fracture and the remaining root can be endodontically treated if the root is to be retained.

If the fracture line is not communicating with the oral cavity, an assessment can then be made of tooth position and tooth mobility. If the coronal fragment is displaced, it should be repositioned and splinted. If the fragment is mobile, it should be splinted. In both scenarios, the teeth should be relieved from occlusion. Non-rigid splinting for less than four weeks is now recommended for most root fractured teeth,⁶⁴ although when excessive mobility of the fragment is encountered, more prolonged splinting may be required. Fractures that occur between the alveolar crest to a distance of 5mm below are the most difficult to manage and have the poorest long-term prognosis.⁶⁵ However, nothing is lost by splinting these teeth and assessing their prognosis over time. Longer splinting times of up to four months are recommended in these circumstances.¹⁸

All root fractures that do not communicate with the oral cavity should be treated as if the pulp is not irreversibly damaged. Endodontic treatment should not be initially undertaken for a tooth with a root fracture, even in the absence of positive pulp sensibility testing, which is a common finding immediately and for some time after a root is fractured.

If the root-fractured tooth is neither displaced nor mobile, then no treatment is necessary in the initial stage, apart from ensuring that the tooth is free from the occlusion in all movements. In the absence of symptoms, follow-up radiographs should be taken at one month, two months and six months following trauma, and then at yearly intervals.¹⁸

Two factors need to be assessed at follow-up examination: pulp sensibility and tooth mobility. In general, if pulp necrosis occurs, it will be confined to the coronal fragment. Should pulp necrosis develop, temporary filling of the root canal with calcium hydroxide for four to six months to the level of the fracture followed by root filling with gutta-percha or MTA^{8,63} to that level is the treatment of choice. Under no circumstances should the pulp be removed beyond the level of the fracture in the first instance as doing so will compromise the long-term success of treatment. As a general rule, the closer the root fracture is to the cervical level the longer the treatment time required. In those rare cases where the apical fragment also becomes necrotic, as would be evident radiographically by the development of a periapical radiolucency as well as a mid-root radiolucency, a decision must be made whether to root fill to the fracture site and to remove the apical fragment, or to include the apical fragment in the root filling. It has been claimed that prognosis is poor if the apical fragment has to be removed, although not all authors agree with this.⁵⁹

If the tooth continues to be mobile after an initial splinting procedure, consideration can be given to either prolonging the splinting time or splinting the crown of the tooth to adjacent teeth in a more permanent manner. Some long-term discomfort to biting on a root-fractured tooth is not unusual. Treatment of root-fractured teeth by the use of

endodontic implants has been recommended in the past as a means to reduce mobility. However, the long-term prognosis for these implants is doubtful and their placement is not recommended.⁴

Luxation injuries

Andreasen⁴ describes five types of luxation injury and a number of studies have investigated the prognosis for luxated teeth.⁶⁶⁻⁶⁹ From an endodontic point of view, the main complicating factors of luxation injuries are pulp necrosis with infection, pulp canal calcification, ankylosis and root resorption. Factors that affect the prognosis of luxated teeth are the degree of displacement, treatment time delay, root maturation and concomitant crown fractures. Most cases of pulp necrosis in luxated teeth become evident within four months. Root resorption often occurs within the first five months after injury and can develop quite rapidly, particularly in immature teeth. Hence, frequent follow-up examination is recommended. In some cases pulp necrosis may appear at a much later date and therefore long-term follow-up is essential.⁷⁰

Concussion

This injury to the supporting structures is characterized by marked tenderness to percussion, but no abnormal loosening or displacement of the traumatized tooth. Only a small percentage of these teeth undergo pulp necrosis (3 per cent) or pulp canal calcification (2–7 per cent).^{12,71} Root resorption is not a feature of concussed teeth.

Subluxation

This injury is characterized by abnormal loosening of the tooth but without displacement. Teeth are tender to percussion and there may be some bleeding in the gingival crevice. Prognosis for subluxation injuries is good. Endodontic management is, however, sometimes necessary.⁷¹ Reported frequency of pulp necrosis ranges from 6 to 17 per cent. Pulp canal calcification has been reported to occur in 9 to 12 per cent of the cases and progressive root resorption in less than 2 per cent.^{12,71}

Extrusive luxation

In this type of luxation, the tooth is extruded from its socket. As such, minimal damage to the socket wall occurs. A recent study involving a paediatric population found that extrusive luxation led to pulp necrosis in 43 per cent of teeth, usually within one year.⁶⁸ Pulp canal calcification was observed in 35 per cent and progressive root resorption in 5.5 per cent of cases.⁶⁸ A direct correlation has been established between the degree of extrusion and the incidence of pulp canal obliteration but not necrosis in a recent study in children.⁶⁸ The incidence of complications with severely extruded teeth was very similar to those of avulsed teeth where the teeth were stored in a suitable physiological medium.⁶⁸

Lateral luxation

Lateral luxation represents eccentric displacement of the tooth in its socket. This type of luxation is accompanied by fracture or comminution of the socket wall and the tooth is usually locked into the new position. The incidence of pulp necrosis in laterally luxated teeth in a paediatric population was found to be 40 per cent, with an additional 40 per cent of teeth demonstrating pulp canal calcification.⁶⁹ Fifty-eight per cent of mature teeth exhibited pulp necrosis and infection following lateral luxation in adults.⁷¹ The incidence of root resorption following lateral luxation has been reported to be 26 per cent.⁷¹

Intrusive luxation

In intrusive luxation the teeth are forcefully intruded into the bone. Because of the direction of displacement, a comminuting fracture of the socket also occurs. The frequency of pulp necrosis is very high. At least 85–95 per cent of mature intruded teeth become necrotic.^{24,67,72} Pulp canal calcification and progressive root resorption are expected to occur in 4 and 48 per cent of cases, respectively.

Treatment of intruded teeth can be complicated by the fact that most intruded teeth are also associated with crown fractures.⁷³ Delayed repositioning leaves roots in intimate contact with bone and this influences the onset of replacement resorption. Thus, mature teeth should be repositioned as soon as possible and the pulps removed immediately or as soon as possible once the soft tissues have healed sufficiently to do so, in order to help prevent the onset of inflammatory root resorption.^{22,74} Although immediate (i.e., surgical) repositioning is the treatment of choice for mature teeth in adults (>17 years of age), orthodontic repositioning is another option for managing such injuries.⁷⁵

Intruded immature teeth behave somewhat differently and more treatment options are available. The apex is open and the bone in children is softer and more malleable. In these teeth, the extent of the intrusion and the presence of associated crown fractures are important prognostic considerations. All intruded teeth in a paediatric population survived for five years if the intrusion was less than 3mm, 90 per cent if the intrusion was between 3mm and 6mm, and only 45 per cent if the intrusion was greater than 6mm.⁶⁷ Almost all surviving intruded immature teeth undergo pulp canal calcification. Pulp necrosis is usually diagnosed within six months but may develop up to two years later in open-apex teeth.^{67,72} In open-apex teeth, awaiting spontaneous eruption has been reported to lead to the best outcomes.⁷⁵ However, careful monitoring must be carried out to ensure that resorptive defects are detected and treated early. Root resorption has been reported to occur in a large number of cases.^{67,72}

It can be seen from the above that luxation injuries result in a much higher incidence of pulp necrosis than do injuries involving fracture of the teeth. As would be expected, the risk of pulp necrosis increased with the

extent of the injury; concussion and subluxation represent the least risk, followed in ascending order by extrusive, lateral and intrusive luxation. Intrusive luxation appears to be the most serious type of injury with regard to the development of pulp necrosis and the development of root resorption. Teeth that have been luxated should be identified and observed over a long period. Teeth with completed root formation demonstrate a greater risk of pulp necrosis than teeth with incomplete root formation. In particular, development of pulp necrosis after injury has been shown to be significantly related to the diameter of the apical foramen.⁷⁶ For extruded and laterally luxated teeth, the smaller the diameter, the greater the probability of pulp necrosis. Intruded teeth with incomplete root development are associated with a much higher probability of pulp survival than teeth with complete root development.

The diagnosis of pulp necrosis following luxation injury needs careful attention. The initial condition of the pulp may be one in which only the nerve supply has been damaged and the potential for revascularization without concomitant neuron-regeneration cannot be dismissed. The extent of apical displacement has been found to be significantly related to the incidence of pulp necrosis for intrusive luxations but not extrusive and lateral luxations.⁶⁷⁻⁶⁹ Sensibility tests, though useful, may be unreliable in luxated teeth. Discolouration and periapical radiolucent lesions are the most important diagnostic features to be noted for subluxation, extrusive luxation and lateral luxation. The presence of inflammatory root resorption is an important factor in establishing the diagnosis of pulp necrosis and infection in replanted and intruded teeth,⁴ and pulp extirpation must be carried out at the earliest radiographic sign of this process occurring.

There is one factor that should not be overlooked when assessing radiographic changes in luxated teeth. While a rare occurrence, transient apical breakdown is believed to be a non-infected apical remodeling process, which can mimic pulp necrosis radiographically and in clinical tests and observations. Andreason⁷⁷ examined 637 cases of luxated teeth and identified this process in 4.2 per cent of teeth. The majority of these teeth demonstrated a periapical radiolucency, as well as colour and/or electrometric sensibility changes. All teeth showed resorptive widening of the apical foramen. All signs and symptoms later returned to normal. Recognition of transient apical breakdown is important if unnecessary endodontic treatment is to be prevented. Transient apical breakdown is more common in mild luxation injuries in fully formed or almost fully formed teeth. A case can be made for observing asymptomatic teeth with early signs of pulp necrosis in selected cases, but only where the clinician is absolutely confident that the patient is likely to comply with frequent recall investigations. Continued root development and calcification within the canal must be regarded as a positive indication of a vital pulp

even in the absence of a positive response to pulp sensibility testing. Regular radiographic examination is necessary. Endodontic therapy must be commenced at the first radiographic evidence of inflammatory root resorption.

Endodontic treatment of luxation injuries

It is generally agreed that for most luxation injuries, with the exception of intrusive injuries in mature teeth, endodontic therapy should be postponed until additional signs of necrosis appear such as colour change and radiographic changes, both in the tooth and the surrounding bone.^{4,17,27} Should the pulp become necrotic and infected, treatment is dependent upon the state of closure of the apex. If apical maturation is complete, standard endodontic treatment is indicated. Should apical development be incomplete, apexification procedures utilizing calcium hydroxide²⁵ and/or MTA²⁷ are indicated.

The first concern in the treatment of luxation injuries should be the repair of the periodontium. Soft tissue injuries and repositioning should be treated before endodontic procedures are contemplated.

Endodontic treatment need not be considered for concussion and subluxation injuries until there are signs of pulp necrosis. However, judicious grinding may be necessary to free the tooth from occlusion. Frequent radiographic examinations and pulp sensibility testing are needed during the follow-up period.

If the root is extruded, careful monitoring of the tooth must be undertaken after repositioning and a period of splinting of two weeks duration. In the event that there has been a delay in repositioning the teeth, gentle orthodontic treatment may be needed to reposition them. Radiographic examination and pulp sensibility testing should be carried out at regular intervals such as: two weeks, one month, two months, six months, 12 months and then on a yearly basis for a number of years.¹⁸ Endodontic therapy should be commenced immediately there is evidence of pulp necrosis or root resorption. While immature teeth can revascularize and can continue root development, which can be seen radiographically, it is not prudent to delay treatment in immature teeth that show any sign of root resorption, as inflammatory root resorption can occur very rapidly. A delay in treatment even for one week can result in loss of substantial tooth structure. In these teeth, pulp extirpation and root filling after calcium hydroxide or corticosteroid/antibiotic therapy is the treatment of choice. In mature teeth, endodontic therapy should be undertaken where there is clinical and/or radiographic evidence of pulp necrosis and infection, or root resorption. Continued lack of reaction to pulp sensibility testing is usually indicative of pulp necrosis, unless there is radiographic evidence of ongoing calcific changes in the root canal system.

Where a tooth has been laterally luxated, it should be repositioned without delay. Again, endodontic therapy is carried out only when there are signs of pulp necrosis

or root resorption. Lateral luxation does not occur without fracture of the alveolar socket. Immediate repositioning, with forceps if necessary, and splinting is therefore recommended. Splinting should be of four weeks duration to allow the fractured bone to heal.¹⁸

Treatment of intruded teeth can be a challenge. Pulp necrosis almost invariably occurs in intruded mature teeth^{11,71,72} and treatment can be complicated by the fact that most intruded teeth are also associated with crown fractures.⁷³ Subsequent re-eruption, if it occurs, may be very slow during which time root resorption may become advanced. Delayed repositioning leaves roots in intimate contact with bone and this influences the onset of replacement resorption. Thus, mature teeth should be repositioned as soon as possible and the pulps removed immediately, or as soon as possible once the soft tissues have healed sufficiently to do so, to help prevent the onset of inflammatory root resorption.^{22,74}

Repositioning intruded teeth is a priority and can occur through spontaneous re-eruption or it may require surgical or orthodontic repositioning. Surgical repositioning or orthodontic repositioning is the treatment of choice for mature teeth in adults (>17 years of age).⁷⁵ A recent review found no significant difference in healing between surgical or orthodontic repositioning of permanent intruded teeth.⁷⁵ Surgical repositioning is preferred where there is complete intrusion and gingival healing may prevent re-eruption or complicate orthodontic repositioning. A surgical technique may be more practical for multiple intrusions where orthodontic anchorage may be an issue. Care must be taken in repositioning these teeth to ensure that the hard tissues are brought down with the tooth and that the soft tissues are sutured into place if necessary.

While orthodontic extrusion has been advocated, it is not always possible as the teeth are often wedged firmly into the bone and attempts to extrude the tooth can lead to intrusion of adjacent teeth. Each situation has to be assessed on its merits and on the state of development of the tooth. Mature teeth that are firmly wedged into the alveolus should be immediately repositioned surgically. In mature teeth, urgent endodontic management should be commenced as soon as practical following repositioning.

Intruded teeth with open apices are more likely to erupt spontaneously and less likely to develop problems of an endodontic origin. As immature intruded teeth can spontaneously reposition themselves in the arch and significantly better healing occurs when this happens, it has been suggested that treatment be delayed for these teeth.⁷⁵ However, if spontaneous repositioning does not appear to be occurring quickly, immature teeth can be brought down by orthodontic or surgical means as soon as possible after trauma. There is an argument for surgically disimpacting these intruded immature teeth from the alveolus to assist with re-eruption. Regular radiographic follow-up at two weeks, one month, two months, six months and

yearly is essential for these teeth as root resorption can occur rapidly in immature teeth.¹⁸ Should any resorption be detected, pulpectomy and treatment with calcium hydroxide or a corticosteroid/antibiotic paste prior to root filling procedures should be urgently carried out. Surgical exposure of the intruded immature teeth to permit endodontic therapy has been proposed to avoid delay in endodontic treatment and the development of inflammatory root resorption.²⁵

Avulsion

Avulsion or exarticulation occurs when a traumatic injury totally displaces a tooth from the socket. Treatment of the avulsed tooth is one area in dentistry where recent research has been applied to greatly improve the prognosis for the long-term retention of these teeth. Andreasen recently reviewed tooth avulsion and replantation.⁷⁸⁻⁸¹ Although the prognosis for an avulsed tooth must always be guarded, replantation as soon as possible followed by a brief period of flexible splinting and endodontic therapy has been shown to be the most effective method of treatment. The shortest extra-oral period (less than 15 minutes), minimum manipulation of the tooth surface and the socket, and the use of an appropriate storage medium have been identified as factors that minimized subsequent root resorption.

The most common reason for unfavourable long-term survival of avulsed teeth is root resorption. A number of factors have been identified as being important in the prevention and management of root resorption associated with avulsed teeth.

Vitality of the periodontal ligament and tooth socket

Vitality of the periodontal ligament cells is a factor that greatly affects the healing of replanted teeth. When the vitality of the periodontal ligament cells is lost, replacement resorption usually occurs. There is a relationship between the total area of root surface where the cells have become necrotic and the amount of replacement resorption generated.⁸²

Extra-oral time

It has been clearly established that the length of extra-oral dry time and the stage of root development are the most critical factors associated with root resorption.⁷⁸ The critical dry time where a statistically significant increase in root resorption was observed was 15 minutes in one study although just five minutes of dry time was sufficient to increase the incidence of resorption in another study.⁸³ Teeth that are replanted immediately have the best long-term prognosis and the least incidence of root resorption.

One animal study⁸⁴ has suggested that removal of a non-vital periodontal membrane with solutions such as sodium hypochlorite may slow the rate of resorption in teeth for which replantation has been delayed (e.g., more than 60 minutes), but the findings of this study have not been corroborated in human material. The

International Association for Dental Traumatology¹⁸ does not recommend pre-soaking in sodium hypochlorite but it does suggest that the roots of avulsed teeth with delayed replantation times (more than 60 minutes) should be scrubbed clean with gauze to remove necrotic material and that the teeth should then be soaked in a 2% sodium fluoride solution for 20 minutes before replantation in order to help delay the inevitable onset of replacement resorption and ankylosis.

If replantation has been delayed, endodontic therapy can be commenced after replantation in mature teeth but, for technical reasons, there may be an advantage in carrying out the endodontic therapy prior to replantation in teeth with open apices and which have experienced long delays (greater than 60 minutes) before replantation.¹⁸

Storage medium

As most avulsed teeth are not replanted at the site of the injury and few patients can receive treatment within 15 minutes, a suitable storage medium to maintain the health of the periodontal ligament cells is critical. In studying periodontal ligament healing associated with replanted teeth in monkeys, Andreasen⁸⁵ varied the extra-alveolar time periods and the storage media. He established that if the teeth cannot be replanted immediately, then storage in saliva or saline solutions significantly reduced the amount of root resorption. Storage in tap water should be avoided as this causes the cells to swell and become necrotic. Acceptable solutions appear to be milk, contact lens solution,⁸⁶ Hanks Balanced Salt Solution and saliva.⁸⁷ Wrapping the tooth in polyethylene film (e.g., Glad Wrap) has been suggested where teeth cannot be replaced immediately and if storage solutions are unavailable.

Splinting

Splinting procedures do not significantly improve periodontal healing. Longer splinting times (greater than 10 days) tend to hasten the resorption process, particularly if inflexible splints are used. It is probable that functional stimulation plays a role in repair.^{14,88}

Socket preparation

Transplantation experiments indicate that the vitality and integrity of the tooth socket is a factor to be noted in the development of root resorption, although the length of time out of the socket appears to be more critical. Curettage of the socket is not necessary, although doing so has no major effect on the replanted tooth. However, gentle irrigation of the socket to remove any blood clots prior to replantation is thought to be better than curettage and may be necessary if there has been a time delay in replanting the tooth.²¹

Antibiotic therapy

Systemic administration of antibiotics is generally recommended in order to prevent the harmful effects of

bacterial contamination,⁴ although the evidence to support this is limited. Experimental animal studies have reported that systemic antibiotics decrease the incidence of inflammatory root resorption but have a limited, or no, effect on the pulp.⁸⁹ Recent research has focused on the effect of topical antibiotic therapy with promising results in animal models. Topical doxycycline and minocycline applied to the root surface before replantation have been found to increase the chance of pulp revascularization in dogs⁹⁰ and to decrease the chance of inflammatory root resorption and ankylosis in monkeys.⁹¹ The use of intracanal antibiotics and corticosteroids immediately after replantation appears to halt the progression of inflammatory root resorption, although replacement resorption still occurs to some extent.⁷⁴

Effect of endodontic therapy

Endodontic therapy involving obturation with gutta-percha or the placement of calcium hydroxide dressings at the time of replantation delays periodontal healing and hastens replacement resorption in mature teeth. Endodontic therapy should be delayed until the initial period of soft tissue healing takes place.⁴ However, since revascularization rarely occurs in mature teeth, and as pulp necrosis contributes to inflammatory root resorption, it has been recommended that in mature teeth pulps should be extirpated as soon as possible⁷⁴ or after initial periodontal healing has occurred (seven to 10 days).^{18,21,92} Recently, Bryson *et al.*⁷⁴ have suggested that pulps in avulsed, mature teeth should be removed immediately after the teeth are repositioned and that an intracanal dressing with a corticosteroid/antibiotic paste should be placed in order to prevent the initiation of inflammatory root resorption.

Contamination of the root surface

Contamination of the root surface has been found to be a prognostic indicator for root resorption. The prevalence of resorption in teeth replanted without visible contamination has been reported to be 57 per cent, whereas 75 per cent of teeth that were washed and 87 per cent of those that were rubbed clean underwent resorption. When teeth were replanted with visible contamination still present, 100 per cent exhibited resorption.⁸³

Stage of root development

The replantation of avulsed teeth with immature root development has been the subject of review.⁹³ As the pulps in a small percentage of replanted immature teeth may survive, it is recommended that endodontic treatment should be delayed in these teeth to establish whether root formation continues. Revascularization appears inversely proportional to root length. However, external inflammatory resorption progresses very rapidly in immature tooth roots. Thus, regular clinical and radiographic examinations at short intervals are recommended to establish whether resorptive processes

have been initiated. Great care should be taken in delaying treatment if patient compliance to attend recall examinations cannot be assured. Calcific changes within the pulp canal imply that the pulp has remained viable at least for some time following the injury.

Endodontic treatment of avulsed teeth

It has been previously recommended that in mature teeth, endodontic therapy should be commenced seven to 10 days following replantation.^{18,21,92} However, it would now seem that pulp extirpation should be carried out as soon as possible to prevent the initiation of inflammatory root resorption.⁷⁴ The canal should be debrided, dressed with a corticosteroid/antibiotic⁷⁴ or calcium hydroxide paste preparation for one to three months, after which time the canal can be obturated and the access cavity sealed. Follow-up radiographs should be taken at regular intervals of one, three, six and 12 months.¹⁸ Longer-term follow-up radiographs are desirable, as a number of authors have reported that resorption may occur up to 10 years after avulsion.

In immature teeth, when the time out of the mouth is short *and* the apex is open, revascularization of the pulp may occur. Endodontic therapy can be delayed to establish whether revascularization will occur but only if patient compliance for follow-up treatment is assured. Regular follow-up is essential and apexification procedures should be carried out at the first sign of resorption, discolouration, the presence of a draining sinus or periapical bone loss. The root canal should be accessed so the infected tissue and debris can be removed and the canal can then be filled with calcium hydroxide. Root filling procedures involving gutta-percha and/or MTA can be carried out at a later date.

Root resorption

Resorption is a common sequel to dental trauma and may be caused directly by the traumatic incident or indirectly through subsequent infection. Andreasen has described three types of resorption following trauma: surface resorption, replacement root resorption and inflammatory root resorption.⁴ Root resorption has also been described as being as ankylosis-related and infection related.¹⁸ Heithersay has extensively reviewed root resorption and proposed a new system of classification of these defects, as well as describing a range of treatment options for these lesions.⁹⁴⁻⁹⁶

The three most common resorptive patterns seen in traumatized teeth are surface, replacement and inflammatory resorption. Surface and replacement resorption are trauma induced, whereas inflammatory root resorption is caused by the combination of traumatic injury and infection of the necrotic root canal system.

Surface resorption is believed to be a self-limiting response to a localized injury to the periodontal ligament or cementum. In traumatized teeth this type of resorption occurs more commonly in the apical portion

of the root and may be seen as a shallow rounding of the tooth shape.

Replacement root resorption results in the replacement of tooth structure by bone and can be recognized radiographically by the diffuse nature of the resorptive defect, the disappearance of the periodontal space adjacent to the area of the resorption and the lack of a bony defect adjacent to the resorptive defect. Replacement resorption is generally associated with replanted or luxated teeth. It is a progressive type of resorption and the prognosis is very poor. It is thought to be initiated by damage to the periodontal ligament leading to a fusion between dentine and bone with progressive replacement of the dentine by bone.⁹⁷ In most instances the majority of the root becomes involved over time and, in these cases, the clinician may elect to allow the process to continue to its inevitable end result – i.e., total destruction of the root. This process usually takes about five years but may take much longer, especially in older patients.

Inflammatory root resorption occurs entirely as a result of a necrotic and infected pulp. It can be recognized radiographically by the development of a radiolucency in the bone adjacent to the resorptive defect. Removal of the infected pulp tissue, dressing with an anti-clastic medicament (such as Ledermix[®] paste) and subsequent filling of the root canal with gutta-percha will usually halt the resorptive process.

Inflammatory and replacement resorption may occur together in the one traumatized tooth. Endodontic treatment may halt the inflammatory resorption but the replacement resorption, once initiated, is generally progressive.

Less commonly, traumatic injury may cause other hyperplastic forms of tooth resorption. Heithersay describes these as internal replacement resorption and invasive coronal, cervical or radicular root resorption. Treatment options for these types of resorptive effects have been extensively described.⁹⁶

Recently, the desirability of replanting avulsed teeth with long dry times in young patients has been brought into question due to the inevitable complication of ankylosis, infra-occlusion of the tooth and disturbances in alveolar growth.⁹⁸ Additionally, since removal of mature ankylosed anterior teeth is sometimes difficult and destructive to the supporting bone, early removal of ankylosed and resorbing mature teeth may be warranted if implant replacement is to be carried out at a later date. Alternatively, root submergence (decoronation) in the growing patient allows continued alveolar development and maintains bone for subsequent implant placement when growth is complete.

Endodontic treatment of teeth with resorptive defects

Surface resorption is self-limiting and does not generally require treatment. Frequent clinical and radiographic review is necessary, however, to confirm that inflammatory and replacement resorption are not occurring in these teeth.

Where resorption has been initiated in traumatized teeth, replacement resorption cannot be treated effectively. Nevertheless, as replacement and inflammatory root resorption can occur together, endodontic therapy to remove necrotic and infected pulps from resorbing teeth is warranted. As an interim measure the teeth can be dressed with a corticosteroid/antibiotic paste or calcium hydroxide, or it can be root filled. Each case has to be treated on its merits. Treatment of resorbing traumatized ankylosed anterior teeth often requires multi-specialty treatment planning. Before extensive endodontic management is contemplated, the options of extraction, prosthetic replacement, maintenance of the space for future prosthetic replacement, orthodontic space closure, autotransplantation and surgical root submergence must be contemplated. In younger patients, where retention of a submerging ankylosed tooth can retard alveolar growth, root submergence (decoronation) should be contemplated once evidence of submergence is noted.¹⁸ In contrast, in older patients, extraction and replacement with an osseointegrated implant is an option.

Inflammatory resorptive defects are treated by immediate pulp extirpation and the use of corticosteroid/antibiotic or calcium hydroxide intracanal dressings until there is evidence of bone healing. Since any delay in treatment increases the surface area of the root that needs repair, urgent and early treatment is recommended. Root canal disinfection and medication removes the cause of the resorption. Provided endodontic treatment is initiated early enough, most inflammatory resorptive defects can be treated conservatively.

Treatment of external invasive root resorption is dependent upon the position and extent of the resorptive defect. Heithersay⁹⁴⁻⁹⁶ has recently described treatment options involving the careful application of trichloroacetic acid BP (90% solution) from either an internal or external approach as a means of managing some invasive resorptive defects.

Pulp canal calcification

Calcification of the root canal (commonly referred to as pulp canal obliteration, or PCO) is a common sequel following luxation injuries to permanent teeth, particularly teeth that have been injured before their root formation has been completed.⁹⁹ Abbott and Yu¹⁰⁰ have discussed the terminology regarding this condition and they have recommended the use of the term “calcification” (rather than “obliteration”) as it more accurately describes what is happening, or what has happened, within the root canal. Obliteration implies complete blocking or elimination of the canal which is unlikely, even in a tooth that radiographically appears to have no root canal present.

Clinically, a yellowish discolouration of the crown may be observed. Pulp canal calcification is also a common occurrence in root-fractured teeth occurring

principally in the region of the fracture, and in the apical fragment. It may also occur in teeth associated with alveolar and jaw fractures.

In most traumatized teeth that have pulps undergoing calcification, the hard tissue is deposited longitudinally along the dentinal walls of the pulp canal, which gradually diminishes in size until it can barely be observed radiographically. In view of the manner of calcification, there is always a canal present and endodontic management is usually able to be performed, if it becomes necessary, by an experienced clinician. On the other hand, however, pulp canal calcification that occurs in traumatized, root-fractured, open-apex teeth and in immature canine teeth that have had prolonged orthodontic treatment is often irregular and these teeth are difficult to manage endodontically if such treatment becomes necessary.

Fortunately, only a small percentage of teeth with pulp canal calcification develop pulp necrosis and become infected.¹⁰¹ Pulp necrosis and infection is more likely to occur in teeth in which the pulp appears almost totally calcified, in teeth with completed root formation that have had severe periodontal injury at the time of trauma, and in teeth that have shown “rapid” calcification of the canal after injury. Pulp necrosis and infection may occur up to 20 years following injury. However, the pulps in most teeth with pulp canal calcification remain healthy and do not require endodontic treatment. Assessment of the status of the pulp is difficult since these teeth do not usually respond to thermal pulp sensibility testing. Most, however, do respond to electrical stimulus, and therefore electric pulp sensibility testing is the desirable method for assessing the status of the pulp in calcified teeth.

Endodontic treatment of teeth with pulp canal calcification

Treatment of teeth with pulp canal calcification presents a dilemma. A number of authors have proposed that for endodontic technical reasons and for prevention of tooth discolouration, these teeth should be root filled once the calcification process is detected. Endodontic procedures are certainly easier if undertaken at this stage. However, most of the recent literature indicates that endodontic treatment is unnecessary unless the tooth is symptomatic or there is radiographic evidence of pulp necrosis and infection³ – i.e., a periapical radiolucency. Proponents of the latter course of action base their opinions on histological studies which indicate that the calcific changes do not warrant pulp extirpation and that a remnant of the canal is always present.

The presence of a periapical radiolucency implies that a canal is present. Although the location and negotiation of the canal may be difficult, it is invariably present and is negotiable in almost all cases. With care, the orifice to a trauma-induced calcified canal can invariably be located in the crown of the tooth, above

the cervical margin. A “catch” on the floor of the pulp chamber, felt with an endodontic explorer or file, will generally indicate the position of the canal, as will a colour change in the middle of the root. As the calcific material is generally softer than regular dentine, carefully “picking away” at this softened material with a suitable explorer and/or the use of rotary nickel titanium instruments will often remove sufficient material to reveal the opening of the root canal system. Negotiation of the canal requires patient exploration of the floor of the pulp chamber with a bright light and radiographic assessment. Transillumination using a light source placed on the cervical area of the tooth under the rubber dam is invaluable. Pre-operative radiographs can assist in determining the level at which the canal is to be found. Increasing the exposure of the pre-operative radiograph may reveal the canal outline more clearly.

Where difficulty is experienced in locating a calcified canal in a traumatized tooth, it is usually because the canal has been bypassed rather than that the canal is not present at the level of the search. If an undetected canal is visible radiographically at the level of exploration, it must be assumed that the canal has been bypassed and exploration deeper in the root is not advisable. As lingual access to a root canal often directs instrumentation in a labial direction, a more lingual approach may assist in locating the canal. Dentine softening agents have been proven to be ineffective as aids for the location of calcified canals. Early referral to a specialist endodontist is recommended if difficulties are experienced in locating canals in calcified teeth. A surgical approach to the management of these cases has also been advocated but this should only be considered when conservative attempts to locate and negotiate the canal have been unsuccessful, and such surgery should only be carried out by practitioners with appropriate training, such as a specialist endodontist.

The immature tooth with pulp necrosis and infection

A large number of different apical configurations can result if an immature tooth with an open apex is traumatized. Continued root development, apical doming, in-growth of bone, and aberrant root formation have all been reported. Repair appears to be more related to the creation of an environment conducive to repair rather than the type of medicament used.

The diagnosis of pulp necrosis and infection in an immature tooth is often difficult. Radiographic changes may be difficult to see. The clinician often has to rely on an assessment of other signs and symptoms, such as the presence of acute or chronic pain, tenderness to percussion, increased mobility, discolouration of the crown, or the presence of a draining sinus tract. Radiographic comparison of the root formation of the tooth in question with its contra-lateral tooth is helpful to establish if root development is continuing at the normal rate for that patient. Calcific changes indicate that the pulp is vital, or at least it maintained vitality

for some time after the injury. External inflammatory resorption indicates that the pulp is necrotic and infected, and in need of urgent treatment. Apical remodeling after luxation injuries may indicate that revascularization of the pulp is occurring, or that it has occurred. In general, erring on the side of caution through observation and review is desirable, but great care should be taken when doing this if the tooth was avulsed or intruded, and also when patient compliance with recall examinations is questionable.

A number of studies have suggested that long-term dressing of root canals with calcium hydroxide may weaken the dentine,¹⁰¹ thus early restoration of immature non-vital teeth with MTA has been suggested as an alternative treatment protocol.^{103,104}

Endodontic treatment of immature teeth with pulp necrosis and infection

Once pulp necrosis and infection has been established, apexification procedures need to be initiated. The access cavity preparation should be made large enough to encompass the larger than normal underlying pulp and to allow access of endodontic instruments to the divergent walls. Cleaning should be carried out with great care using copious amounts of irrigant, such as sodium hypochlorite. Reliance on irrigation to remove debris rather than filing is important, as the canal walls in the apical region are thin and fragile. Over-zealous use of files may damage the walls. An endodontic ultrasonic device operated in a canal full of sodium hypochlorite can help remove debris, but care should be taken to ensure that the ultrasonic instrument does not compromise the walls of the canal.

Teeth with infected root canals and open apices are now routinely treated with calcium hydroxide root induction techniques followed by orthograde gutta-percha or MTA root filling techniques. The use of propriety corticosteroid/antibiotic pastes can have a role in initial management to control the apical periodontitis and then once the canal has been fully debrided and the tooth is symptom-free, calcium hydroxide can be placed into the canal using a spiral filler or a proprietary injection syringe. It is imperative that the access cavity then be sealed adequately while apexification takes place. A "double seal" with Cavit® and a stronger restorative dental material is recommended in order to prevent breakdown of the temporary restoration which can lead to re-infection of the canal and subsequently to further apical periodontitis.

Apexification can take from six to 24 months. The role of the medicament is uncertain and apexification has been reported to occur with a number of different paste formulations including tricalcium phosphate, zinc oxide and antibiotic pastes. Continued root development and apical doming can also occur when the canal has been instrumented and left empty or, occasionally, if no treatment at all has been performed.

Regular radiographic assessment is necessary to monitor progress of apexification. The calcium hydroxide should be replaced if apexification is not proceeding, or if the material has resorbed more than one-quarter of the way into the canal space. If the calcium hydroxide is left in the canal for too long without replacement, then apexification may not occur.

As the apical portion of the canal is often larger than the coronal portion and since the cross-section of the canal is much wider in the labio-lingual (or labio-palatal) direction than mesio-distally, a softened gutta-percha root filling technique should be used to fill the canal. Care should be taken not to apply too much pressure during root filling since this may dislodge the apical dome. In addition, the amount of heat used should be limited since the root walls are thin and the heat may be transmitted to the periodontal ligament with potential for adverse effects.

Restoration of an immature tooth that has undergone apexification is difficult as the pulp space is large and divergent, and the remaining root structure will be weak. Subsequent fracture of the root is a possible sequel to apexification procedures,¹⁰⁴ especially if there is any further trauma to the tooth although it can also occur during normal function. The patient, and his/her parents, should be warned of this possibility before treatment is commenced. It has been recommended that these teeth should be strengthened by the use of an intracanal acid-etched composite resin restoration.^{106,107}

CONCLUSION

The endodontic management of traumatized permanent anterior teeth has been reviewed and recommendations have been presented for each type of injury. The management of dental injuries is an evolving science. Some traditional treatment options have stood the test of time and are still valid to this day. Others have been reviewed and modified with the passage of time, as new science and new materials evolve to prove, disprove or facilitate approaches to the management of these injuries. Practitioners need to always be aware of changes that occur from time to time with respect to the recommendations for treatment, and of scientific studies that support or disprove treatment rationales. Regrettably, the amount of good evidence based research data on which to base treatment decisions is still lacking for most injuries to the teeth. Thus, while this paper has reviewed the endodontic management of traumatized anterior teeth in the light of past and present scientific studies, it is inevitable that some of the proposed recommendations will themselves be modified as new science reviews the effectiveness of treatment methods, and new materials and techniques develop to facilitate treatment.

Dental trauma rarely involves just a single tooth. A typical injury may involve multiple injuries to both the teeth and the supporting tissues. Recommendations for single tooth treatment may not always be appropriate for multiple adjacent injuries. Treatment decisions still

need to be based on practicality and experience, as well as an understanding of the literature.

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