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Indications for root canal treatment following traumatic dental injuries to permanent teeth

PV Abbott*

*UWA Dental School, The University of Western Australia, Perth, Western Australia, Australia.

ABSTRACT

The dental pulp may respond favourably or unfavourably to traumatic dental injuries. The most serious unfavourable responses are pulp necrosis and infection of the root canal system. These cause apical periodontitis and/or external inflammatory resorption of the tooth. The following injuries require root canal treatment as part of their emergency management—(A) complicated crown fractures (but some may be suitable for conservative pulp treatments, such as pulp capping, partial pulpotomy or pulpotomy), (B) complicated crown-root fractures, (C) supra-crestal coronal third root fractures and (D) injuries where pulp necrosis is predictable or highly likely to occur AND where there has been damage to the root surface and/or periodontal ligament with the aim of preventing external inflammatory resorption. This latter group of injuries are avulsion, intrusion, lateral luxation with a crown fracture, extrusion with a crown fracture (all in fully developed teeth) plus avulsion with a crown fracture and intrusion with a crown fracture (both in incompletely developed teeth). All other injuries should not have root canal treatment commenced as part of the emergency management, but they must be reviewed regularly to monitor the pulp for any adverse changes to its status, particularly pulp necrosis and infection of the root canal system.

Keywords: Dental traumatic injury, root canal treatment, complicated fracture, inflammatory resorption, pulp necrosis.

Abbreviations and acronyms: IADT = International Association of Dental Traumatology; TDI = traumatic dental injury.

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CLINICAL RELEVANCE

The dental pulp may be affected by traumatic dental injuries. Some injuries require immediate commencement of root canal treatment (RCT) during their emergency management while others do not require immediate RCT. Teeth with complicated crown fractures, complicated crown-root fractures and sub-crestal coronal third root fractures require immediate RCT to enable restoration of the tooth. Some luxation and avulsion injuries require RCT to prevent external inflammatory resorption. The pulps of teeth with all other injuries should be reviewed regularly and RCT should only be done when there are definite signs of pulp necrosis AND infection of the root canal system.

INTRODUCTION

It has been estimated that almost one billion people in the world have suffered a traumatic dental injury (TDI) at some time in their life.[1] This figure represents about 12.5% of the world's population. Approximately 900 million of these injures have occurred in people aged 7–65 years old and approximately 180 million in children aged between 1 and 6 years old.[1] The former group implies trauma to the permanent dentition since most TDIs involve the maxillary anterior teeth, particularly the maxillary central incisors. The latter group mainly implies trauma to the primary dentition, although some children in this group may have had trauma to their permanent maxillary central incisors since these teeth have often erupted before the end of the child's 6th year.[2]

A prospective study in Denmark reported that one in every two children had sustained a TDI by the time they were 14 years of age with 30% of the children having injuries to the primary teeth and 22% had injuries to permanent teeth.[3]

Dental traumatic injuries are the fifth most common condition in human beings and the second most common oral condition. Dental caries is the most common condition or disease in humans as well as the most common oral condition. Tension-type headaches are

the second most common condition overall followed by iron deficiency anaemia, age-related and other hearing loss and then dental traumatic injuries.[4,5]

The above data indicate that TDIs are very common. Hence, dentists must be educated, and competent, to manage these injuries in an effective, efficient and predictable manner. However, unfortunately and despite the freely available International Association of Dental Traumatology guidelines which were first published in 2001,[6] numerous studies have reported that the level of knowledge of TDI management among dentists in many different countries throughout the world is average or poor, particularly regarding the emergency management of TDIs.[7-21] As an example, the average score obtained by dentists in Southern Brazil[18] was only 5.87 ± 1.57 out of a possible score of 12 in a survey regarding the management of TDIs according to the International Association of Dental Traumatology (IADT) guidelines. This score was based on questions about the emergency management of 12 TDI scenarios. This low score was obtained despite the participants self-rating their knowledge about TDIs as 'Acceptable' (35%), 'Good' (53%) or 'Very Good' (9%). Only 3% of participants self-rated their knowledge as 'Poor'.[18] In a similar study of Australian dentists that used the same 12 questions,[21] the average score was only slightly better (7.6 ± 1.9) despite the participants self-rating their knowledge as 'Poor' (8%), 'Acceptable' (51%), 'Good' (28%), 'Very Good' (12%) or 'Not Specified' (1%). The average scores for the 12 case scenario questions within each of these groups did not correlate well their self-reported knowledge level except for the 'Very Good' group which had the highest average score of 8.52 ± 2.64.[21]

These reported low levels of knowledge about TDI management among dentists are a particular concern as it implies that appropriate management may not be provided when patients present to many dentists following a TDI. If the correct, and appropriate, emergency management is not provided, then the long-term prognosis of the tooth is likely to be seriously compromised. Hence, it is imperative that all dentists maintain their knowledge about TDIs and be prepared to provide emergency and follow-up treatment according to accepted guidelines and/or other research findings.[21]

One particular aspect of TDI management that dentists are often uncertain about is whether or not root canal treatment is required, and if it is necessary, then when should it be performed.[21,22] Hence, the aim of this review is to provide guidance to dentists about managing the dental pulp following TDIs to permanent teeth. The management of the pulps of primary teeth following TDIs is beyond the scope of this review.

TISSUE RESPONSES TO TRAUMA

It is essential to understand the various responses of the tissues that are injured when a TDI occurs. The tissues can be divided into three groups—the dental pulp, the peri-radicular tissues (periodontal ligament, alveolar bone) and the soft tissues of the mouth (gingivae, mucosa).[23,24] Each of these tissues is unique and each has a variety of favourable and unfavourable responses to TDI's with many factors determining the responses – such as the type of injury, the degree of displacement of a tooth, the stage of root development, the emergency management, the presence of caries and the presence of restorations in the tooth. In addition, the response of one tissue can affect other tissues – for example, some dental pulp responses, especially pulp necrosis and infection, determine the responses of the peri-radicular tissues.[23,24]

The various responses of the three groups of tissues have been reported in several publications.[23,24] The soft tissue responses will not be discussed in this review as they are not usually directly related to the dental pulp responses following trauma. The following discussion will focus on the responses of the dental pulp and those peri-radicular tissue responses that are directly related to the responses of the pulp.

Responses of the pulp and root canal system

Table 1 summarises the various possible pulp responses following trauma to a tooth. These

Table 1. Favourable and unfavourable responses of the dental pulp and root canal system following trauma to a tooth (adapted from Abbott & Castro Salgado[23] and Yu & Abbott[24])

Favourable responses	Unfavourable responses

• Recovery and return to normal
• Tertiary dentine formation
• Pulp revascularization
• Pulp fibrosis
• Pulp canal calcification
	• Acute inflammation (pulpitis) that does not resolve:
	  ○ Within a few days
	  or
	  ○ Following emergency conservative pulp treatment
	• Chronic inflammation (pulpitis)
	• Pulp necrobiosis
	• Pulp necrosis:
	  ○ Without infection
	  ○ With infection
	• Pulpless and infected root canal system
	• Internal tooth resorption
	  ○ Surface
	  ○ Inflammatory
	  ○ Replacement
	• Combinations of the above:
	  ○ *Simultaneously and/or*
	  ○ *Sequentially over time*

responses can be broadly categorised as favourable or unfavourable responses.[23,24]

The favourable responses do not require endodontic intervention and teeth with these responses should simply be monitored with regular reviews for as long as possible. Such reviews are essential because initially favourable responses following a TDI can become unfavourable over time as a long-term result of the injury. Unfavourable responses that occur later are most commonly due to bacterial ingress into the tooth and pulp through infractions or breakdown of the restoration that was placed to restore a fractured tooth.[23,24]

Unfavourable responses of the pulp following a TDI are generally related to pulp necrosis and infection of the root canal system.[23,24] These responses will require endodontic intervention with the exact type of intervention being dependent on various factors as discussed below. The timing of endodontic intervention is important, and this is also discussed below.

Pulp necrosis will not always be associated with an infected root canal system.[24] Instead, it may be a result of severing of the apical blood supply during an injury, such as a luxation or avulsion – this could be considered as 'instant necrosis'. Hence, a necrotic pulp is not in itself an indication for a tooth to have root canal treatment.[24] Figure 1 is an example of a tooth that is likely to have pulp necrosis but there are no signs of the root canal system being infected and therefore root canal treatment is not indicated – however, the tooth should be regularly reviewed.

A necrotic pulp may become infected at a later stage so any tooth that has been diagnosed as having a necrotic pulp should be regularly reviewed for signs of infection of the root canal system. In order for the necrotic pulp to become infected, the tooth has to either be contaminated during the injury or during the immediate post-injury period, or there has to be an entry pathway for bacteria to reach the pulp—such as via an infraction, a crack, a fracture or an inadequate restoration with marginal breakdown.[24,25]

The various pulp responses may occur individually, or in various combinations.[24] When there are combinations of responses, they may occur simultaneously or sequentially over time. Figure 2 is an example where both simultaneous and sequential responses occurred over time following a lateral luxation and crown infractions eight years prior to when the radiograph was taken. In this case, the pulp must have initially recovered and functioned normally since pulp canal calcification is evident. Then, subsequently at some time bacteria entered the tooth (probably via the infractions, or possibly where the infractions had progressed to become cracks) which led to pulp necrosis and infection of the root canal system and this in turn led to chronic apical periodontitis. In this case, the apical periodontitis was chronic while there were no symptoms but then the patient developed symptoms suggesting that there was secondary acute apical periodontitis which is why the patient sought dental care. The simultaneous responses were the initial recovery and return to normal of the pulp. Later simultaneous responses were the pulp necrosis and infection of the root canal system. The sequential responses were the pulp canal calcification after the initial recovery and then the subsequent pulp necrosis.

Fig. 1 Maxillary left central incisor (tooth 21) was extruded when the patient was 12 years old, which was 10 years prior to this radiograph being taken. The patient has had regular reviews since then. The tooth has consistently not responded to either cold or electric pulp sensibility tests since the injury occurred. There have been no symptoms, there are no radiographic signs of apical periodontitis and there are no clinical signs to suggest an infected root canal system. There has been some pulp canal calcification (PCC) within the pulp chamber. Hence, the diagnosis of this pulp since the injury has been *'probable pulp necrosis without any signs of infection'*. In addition, the periapical tissues are clinically normal. An alternative explanation could be that the pulp's blood supply recovered but the nerve supply did not recover which explains the lack of response to pulp sensibility tests. Although the PCC may explain the lack of current responses to pulp sensibility tests, the lack of responses has been consistent since the injury occurred, so the above diagnoses are more likely. Root canal treatment is not indicated, but the tooth should continue to be reviewed regularly as future infection of the root canal system is possible.

Responses of the peri-radicular tissues

As in the above example, the peri-radicular tissue responses can be directly affected by the response of the pulp and root canal system. Pulp necrosis, with or without infection, is the main problem that can lead to unfavourable peri-radicular tissue responses.[23,24,26]

Pulp necrosis can lead to cessation of, and/or disturbances to, the root development of incompletely

Fig. 2 Example of both simultaneous and sequential pulp responses following a traumatic dental injury. The mandibular right central incisor (tooth 41) had a lateral luxation and crown infractions eight years prior to when this radiograph was taken. The pulp initially recovered and functioned normally, pulp canal calcification followed before subsequent pulp necrosis and infection of the root canal system. This in turn caused chronic apical periodontitis and later secondary acute apical periodontitis (image reproduced courtesy of Abbott & Yu[74]).

developed teeth. This can occur with or without infection of the necrotic pulp.[23,24]

Pulp necrosis with infection of the root canal system can lead to the following unfavourable peri-radicular responses:[23,24,26]

- Inflammation – apical periodontitis
- External inflammatory resorption – lateral or apical
- Bone loss – apical or lateral, associated with both the above conditions.

Other peri-radicular responses such as ankylosis and external replacement resorption may occur following a TDI[23,24,26] but these will not be discussed as they are not related to the pulp responses.

INDICATIONS FOR ROOT CANAL TREATMENT AFTER TRAUMA TO A TOOTH

In order to determine whether, and when, root canal treatment is required following trauma to a tooth, it is essential to understand the nature of each injury and the specific potential effects of each injury to the pulp and peri-radicular tissues. Root canal treatment is not necessary for the majority of injuries and pulps should ideally be given the chance to recover as this will provide a much better long-term prognosis for the tooth. However, there are some circumstances where root canal treatment will be necessary. These circumstances can be divided into two groups – (1) those requiring immediate root canal treatment as part of the emergency management of the injured tooth, and (2) those that require root canal treatment later during the follow-up of the injuries as a result of subsequent pulp necrosis and infection of the root canal system.

An important aspect of managing all TDI's is to conduct a thorough clinical and radiographic examination which must include both cold and electric pulp sensibility tests.[23,24,27,28] However, some clinicians argue that these tests are unreliable immediately after trauma since the pulp is 'in shock' and will not give reliable responses. Despite this possibility, there is no excuse not to do these simple tests at the time of the initial presentation after trauma since there is evidence that indicates the immediate responses to pulp sensibility tests are good indicators of the long-term prognosis of the pulp[23,24,27,28] – for example, very few fully developed teeth that responded to pulp sensibility tests immediately following concussion with a concurrent crown fracture developed pulp necrosis over time, whereas about 50% of teeth that did not respond immediately after these same injuries developed pulp necrosis and infection of the root canal system within 6 months.[29]

Clinicians should be aware that the results of pulp sensibility tests that are performed immediately after trauma should not be used to diagnose pulp necrosis or to indicate that immediate root canal treatment is required since many pulps may recover (Fig. 3) Instead, the results of immediate pulp sensibility tests should be used as a prognostic indicator (as above) as well as being baseline data to be compared with subsequent tests at review appointments which can alert clinicians to pulp necrosis that can occur later. The immediate pulp test results may also indicate that a tooth has been traumatised when there are no other physical signs of injury.[23,24,27,28]

Injuries requiring immediate root canal treatment

Table 2 summarises the injuries and situations that will either definitely, or very likely, require root canal treatment immediately following traumatic dental injuries as part of the emergency management following a TDI. However, each tooth and each injury must be thoroughly evaluated before the decision is made to remove the pulp as conservative pulp treatments are generally preferred, particularly for incompletely developed (immature) teeth.

Before committing a tooth to root canal treatment, a very important factor to consider is the stage of root development of the tooth at the time of injury because many incompletely developed teeth may be capable of pulp revascularisation.[24,30] This occurs when the

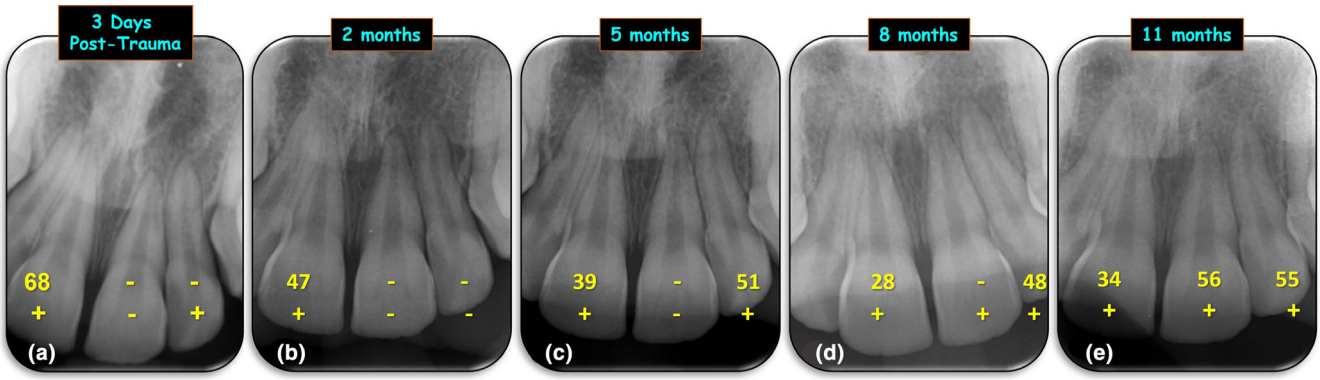

Fig. 3 Example of the variable responses of teeth to pulp sensibility tests following a traumatic dental injury. The maxillary left and right central incisors and the right lateral incisor (teeth 11, 21, 22) had subluxations injuries. The teeth were reviewed regularly with clinical examinations, pulp sensibility tests and periapical radiographs. Radiographs and pulp test results are shown at: (a) 3 days after the injury; (b) Review after 2 months; (c) Review after 5 months; (d) Review after 8 months; (e) Review after 11 months. Footnote – KEY: yellow numerals represent the results of each tooth to electric pulp tests (scale 1–80); yellow '+' sign indicates the tooth responded to a carbon dioxide dry ice test; yellow '-' sign indicates no response to the carbon dioxide dry ice test.

Table 2. Summary of the situations where root canal treatment is required immediately* following traumatic dental injuries as part of the emergency management of the tooth.

Injuries/situations where immediate root canal treatment* is indicated
• Complicated crown fractures
◦ Consider conservative pulp treatment as first choice of management, where feasible
▫ e.g. pulp cap, partial pulpotomy, pulpotomy, partial pulpectomy
◦ RCT only where intra-radicular retention required for restoration of the tooth
• Complicated crown-root fractures
• Supra-crestal coronal third root fractures
• To prevent external inflammatory resorption
◦ See specific injuries listed in Table 3

*Immediate root canal treatment implies that the root canal treatment should be commenced as part of the emergency management of the injury and patient. The entire root canal treatment (i.e. root canal preparation and subsequent root canal filling) does not need to be done as part of the emergency management – simply removing the pulp and medicating the canal is usually sufficient. The root canal treatment can then be continued at a later date when time is available, when the patient does not have any discomfort, and when convenient.

pulp's blood supply recovers through anastomosis of the blood vessels in the periapical region with those in the pulp. Hence, root canal treatment of incompletely developed teeth should be avoided wherever possible to allow for this to occur. Such teeth need regular reviews to determine whether the pulp recovers or not. If the pulp does recover, then the tooth will have a much better long-term prognosis as the tooth root will usually continue to develop and in most cases there will also be pulp canal calcification. Hence, the tooth will ultimately be much stronger as a result of the dentine that has formed during the further development of the root. However, if the pulp does not recover, then root canal treatment will be required, and such teeth will have a higher risk of root fracture because they lack dentine in the critical cervical third of the root.[31]

In most situations, it is not necessary, nor is it desirable, to complete the root canal treatment (i.e. there is no need to do the root canal filling) as part of the emergency management. Simply, the commencement of the root canal treatment by removing the pulp and placing a suitable intracanal medicament will suffice. The remainder of the treatment can be done at a later scheduled appointment when sufficient time is available and there is no urgency.[32] Delaying the mechanical stages of root canal treatment allows the periapical and peri-radicular tissues to heal before subjecting them to the inevitable irritation associated with filing and filling of the root canal system. Not attempting to do the entire treatment is also advantageous to the patient as they will not need to remain in the dental chair for an extended period immediately after having suffered a major injury, which is likely to be a stressful time for them (and their parents if the patient is a child).[33,34]

Once a medicament has been placed in the root canal, the tooth can be temporarily restored. The temporary restoration may be incorporated into the stabilising splint in some cases (Fig. 4). However, some teeth may benefit from doing an immediate root canal filling to enable a temporary restoration to be placed – for example, an extensive fracture where a post may be needed. Fortunately, most teeth that suffer a TDI have a clinically normal pulp prior to the injury and therefore the chance of the root canal system being infected prior to the trauma are minimal. This provides a more favourable situation for a single-visit root canal treatment to be done although clinicians should also be aware of the possibility of periapical

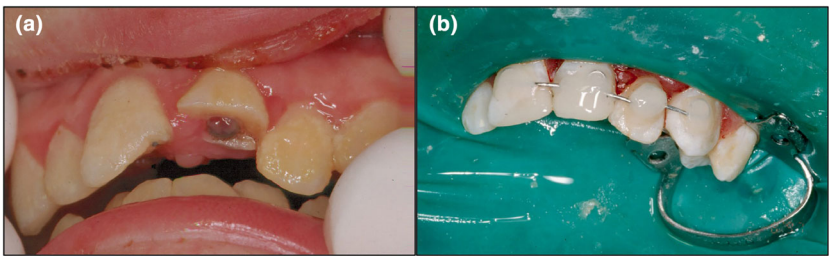

Fig. 4 Example of how dental dam can be used for the emergency management of traumatic dental injuries. (a) Initial presentation of the patient with an uncomplicated crown fracture of the mesial incisal corner of the maxillary right central incisor (tooth 11), a complicated crown-root fracture of the maxillary left central incisor (tooth 21) and lateral luxation of the maxillary left lateral incisor (tooth 22); (b) After local anaesthetic was administered, cotton rolls were placed in the labial sulcus followed by dental dam using the 'cuff technique' with a single clamp on the maxillary left first premolar (tooth 24). The contact point between the maxillary right lateral incisor and canine (teeth 12 and 13) held the other end of the dam in position. Six holes were punched in the dam with each hole overlapping the adjacent hole(s). Footnote – All emergency treatment was then provided with the dam in place – that is the 22 was repositioned, the 21 had the pulp removed and an intracanal medicament was placed, the 11 and 21 had temporary composite resins placed to temporarily restore the crowns, and a splint using wire and composite was placed to stabilise the 22. The temporary restoration of the 21 was incorporated into the stabilising splint. Finally, the dam was removed, the occlusion was checked, and soft tissue lacerations were sutured.

nerve sprouting and postoperative periapical neuropathic pain as a result of the operative trauma created when the nerve fibres are severed as the pulp is removed.[35] It is believed that the use of an intracanal medicament containing a corticosteroid can reduce the chances of this occurring.[36]

Complicated crown fractures

Complicated crown fractures (Fig. 5a) are defined as fractures that involve the enamel, dentine and pulp – that is, where the pulp has been exposed by the fracture.[37]

Not all teeth with complicated crown fractures will require root canal treatment.[32] The decision is usually based on the extent of the fracture and whether or not some form of intra-radicular retention is required to facilitate the restoration of the tooth. Root canal treatment will be indicated if the tooth root is fully developed (mature) and a post or other intra-radicular retention is required. However, if such retention is not required, then the clinician should always consider preserving the pulp through less invasive procedures such as a pulp cap, a partial pulpotomy or a pulpotomy.[32] In the modern era of adhesive dentistry, the need for root canal treatment and posts has been substantially reduced and therefore more conservative pulp treatments are recommended wherever possible.

As above, root canal treatment should be avoided in incompletely developed teeth in order to allow the

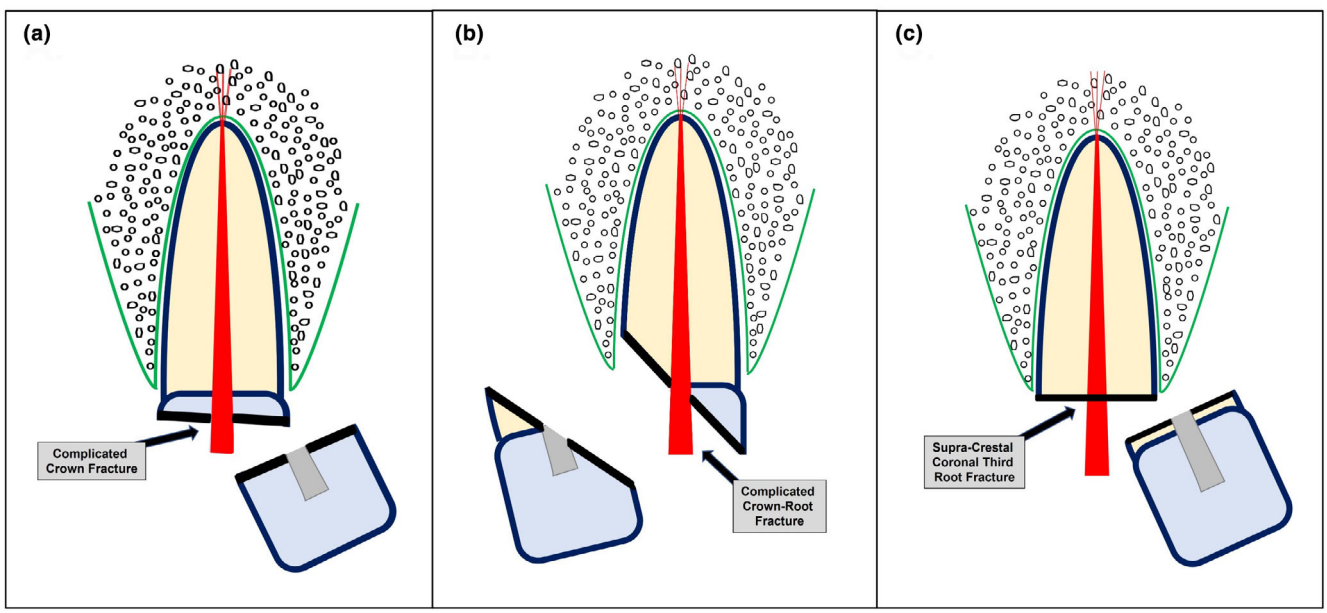

Fig. 5 Diagrammatic representation of injuries that may require immediate root canal treatment as part of the emergency management of the injury: (a) Complicated crown fracture (note some complicated crown fractures can be managed with conservative pulp treatments); (b) Complicated crown-root fracture; (c) Sub-crestal coronal third root fracture.

pulp to recover and for further root development to occur. Hence, treatments such as a pulp cap, partial pulpotomy, pulpotomy or even a partial pulpectomy are recommended as the first-choice treatment for incompletely developed teeth.[32]

Complicated crown-root fractures

Complicated crown-root fractures (Fig. 5b) are defined as fractures that involve the enamel, dentine, cementum and pulp – that is, where the pulp has been exposed by the fracture.[37] This definition implies a much more extensive fracture than complicated crown fractures as significantly more tooth structure has been lost and the fracture extends into the tooth root.

Management of complicated crown-root fractures is highly likely to need to include root canal treatment as part of the emergency or immediate management since intra-radicular retention is usually required. There is usually insufficient coronal tooth structure remaining to allow conservative pulp treatment to be done and to be followed by an adequate restoration.[32]

Teeth with fully developed roots and a complicated crown-root fracture will therefore generally require immediate root canal treatment, followed by an appropriate restoration, according to the extent and location of the fracture, the aesthetic needs, the functional needs, the periodontal situation, etc.

Teeth with incomplete root development and a complicated crown-root fracture pose a difficult dilemma for clinicians as the desire to maintain the pulp to allow further root development must be weighed up against the ability to perform conservative pulp treatment and restoration of the tooth. In such teeth, a partial pulpectomy may be possible and this may allow the use of some of the coronal portion of the root canal to be used to help retain the restoration while preserving the remainder of the pulp in an attempt to promote further root development.[32] This implies sacrifice of the most coronal portion of the pulp which has the distinct disadvantage that no further dentine can form in this region which is where subsequent root fractures tend to occur as a result of the lack of tooth structure.[31] Fortunately, this type of injury is not common in young patients.[38]

Supra-crestal coronal third root fractures

Supra-crestal coronal third root fractures (Fig. 5c) are defined as fractures that occur within the coronal third of a tooth root and the fracture is located coronal to the crestal bone level.[39] Hence, the entire coronal fragment is likely to be extremely mobile and only held in place by a few periodontal ligament (PDL) fibres, or the coronal fragment may have been avulsed.

There is little, if any, chance that the coronal fragment of a tooth can be saved if there has been a supra-crestal coronal third root fracture, since there is insufficient root available to stabilise the fragment and to expect healing to occur.[39] Hence, if such a tooth is to be retained, the pulp will need to be removed and root canal treatment performed to enable a suitable restoration to be placed. Typically, a post and core will be required. The tooth is also likely to need either periodontal surgery (i.e. crown lengthening) or orthodontic extrusion to facilitate restoration of the tooth. Periodontal recontouring surgery is commonly required following orthodontic extrusion as the gingivae will usually be attached to the root and therefore will also be extruded with the tooth root.[39]

The most ideal time to commence the root canal treatment will be at the emergency appointment following the accident. This will also enable the clinician to place a temporary restoration to stabilise the dentition and to address the aesthetics for the patient.

To prevent external inflammatory resorption

External inflammatory resorption is one of the more severe consequences of some specific TDIs.[23,24,26,32] This type of resorption requires two factors to be present – namely, the presence of bacteria in the root canal system PLUS damage to the cementum and PDL, particularly if root dentine has been exposed.[23,26,32,40]

External inflammatory resorption can be distinguished from other forms of resorption by its radiographic appearance, along with the history and clinical findings.[40] The radiographic appearance of loss of tooth structure from the external surface of the tooth root along with the presence of a radiolucency in the adjacent alveolar bone is the key distinguishing diagnostic finding.[26,40] This type of resorption can occur laterally – that is, anywhere along the length of the tooth root – or it can occur apically (Fig. 6). The lateral form is most commonly associated with TDI's whereas the apical form is most commonly associated with a long-standing infection of the root canal system. However, the apical form can also be associated with a TDI and the lateral form can also be associated with long-standing infected root canal systems, especially if there is a lateral canal present.[26,40]

There are several injuries where the above two criteria for this type of resorption to develop are highly likely to occur. Based on many studies that have investigated pulp survival following TDIs, the injuries listed in Table 3 and illustrated in Figures 7 and 8 present a high risk of developing external inflammatory resorption because pulp necrosis is either entirely predictable or highly likely. In addition, teeth with

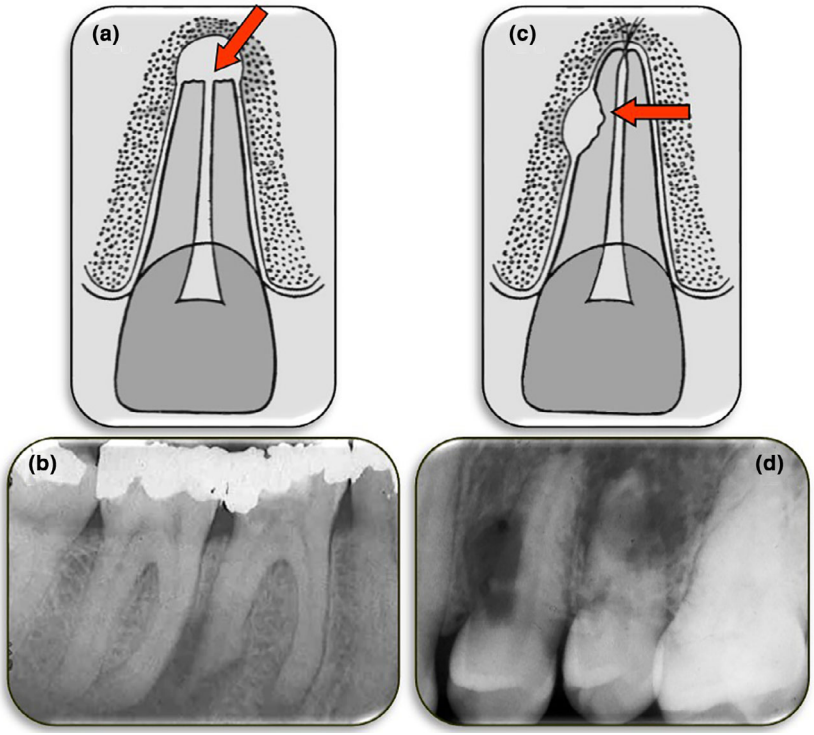

Fig. 6 Diagrams and radiographs illustrating the two types of external inflammatory resorption. (a) Diagram demonstrating external APICAL inflammatory resorption; (b) Periapical radiograph of tooth 36 with extensive external apical inflammatory resorption of both the mesial and distal roots; (c) Diagram demonstrating external LATERAL inflammatory resorption; (d) Radiograph of teeth 24 and 25 with extensive areas of external lateral inflammatory resorption of their roots (images reproduced courtesy of Abbott & Lin 2022[40])

these injuries will have had damage to the PDL and cementum during the injury and possibly also during their replantation or repositioning. Hence, these injuries meet the two criteria required for the development of external inflammatory resorption.[26,32,40]

Prevention of external inflammatory resorption is the most desirable approach as this has fewer complications and it implies that there will be no loss of tooth structure.[26,32] If treatment is delayed until after the resorption has already commenced, then the treatment not only must arrest the resorptive process but it must also stimulate the formation of hard tissue to replace the lost tissue (cementum and bone) as well as encouraging repair of the PDL.

Table 3. Traumatic dental injuries that will predictably, or are highly likely to, have pulp necrosis and infection of the root canal system plus there has been damage to the periodontal ligament and cementum.

Incompletely developed teeth	Fully developed teeth
• Intrusion WITH a Crown Fracture • Avulsion WITH a Crown Fracture	• Extrusion WITH a Crown Fracture • Lateral Luxation WITH a Crown Fracture • Intrusion • Avulsion

Hence, these teeth are highly likely to develop external inflammatory resorption. Therefore, immediate root canal treatment following repositioning/replantation and splinting should be considered for teeth with these injuries in order to prevent external inflammatory resorption (adapted from Abbott & Castro Salgado,[23] Abbott[26] and Cvek *et al.*[32]).

External inflammatory resorption and its management have been comprehensively reviewed in several publications.[26,32,40] These reviews include the rationale for the management approaches and the literature to support them. In summary, there are two approaches – the 'preventive approach' and the 'interceptive approach'.[26,32,40] The 'preventive approach' applies to the injuries listed in Table 3 with the aim of preventing this type of resorption from developing, whereas the interceptive approach is for teeth that already have external inflammatory resorption.

The preventive approach recommended in these publications is to prescribe a short-term course of systemic antibiotics for 1 week (see below for more details) AND to commence root canal treatment immediately after the injured tooth has been repositioned/replanted and stabilised with a suitable splint.[26,32,40] This root canal treatment must be performed under dental dam isolation[26,32] – which can be easily achieved with the 'cuff technique' where a series of holes are punched in the dam and joined as a single opening. A tooth that has not been injured

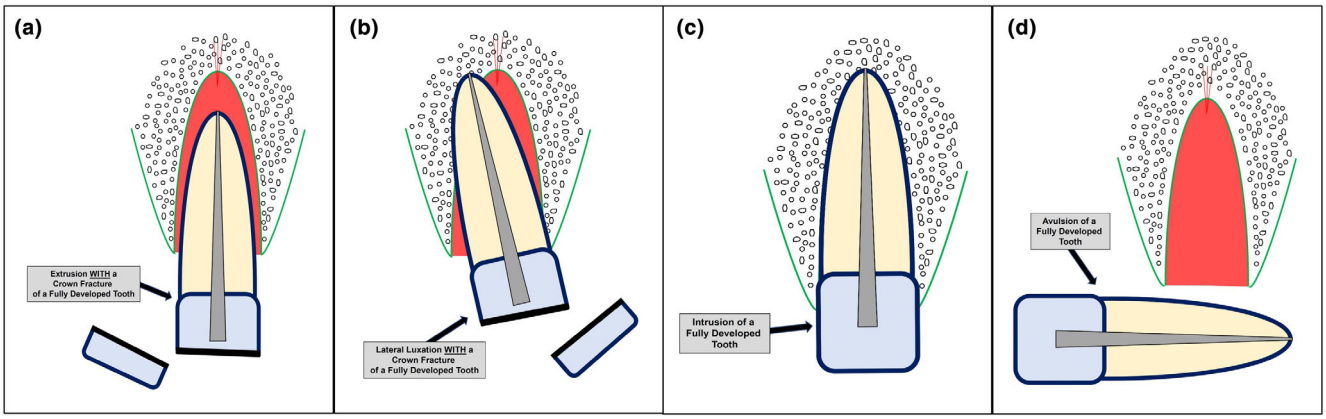

Fig. 7 Diagrammatic representation of injuries to fully developed teeth where pulp necrosis is likely and there has been damage to the external root surface and the periodontal ligament. These injuries require immediate root canal treatment as part of the emergency management of the injury in order to prevent external inflammatory resorption: (a) Extrusion WITH a crown fracture; (b) Lateral luxation WITH a crown fracture; (c) Intrusion; (d) Avulsion.

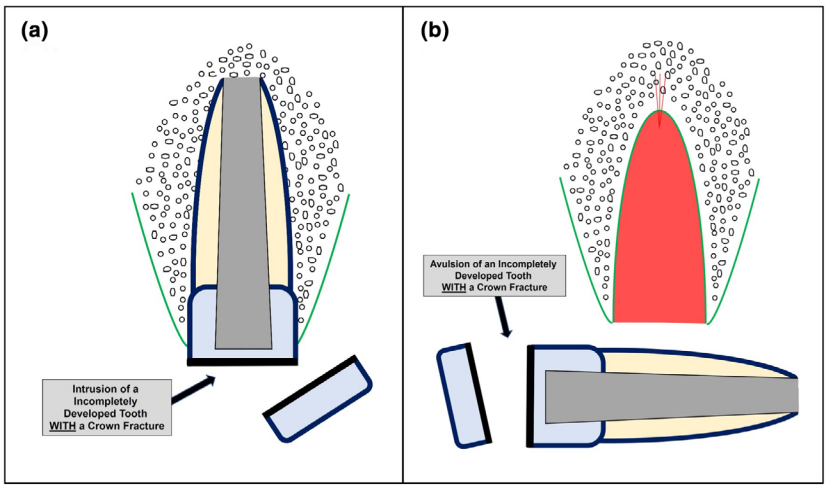

Fig. 8 Diagrammatic representation of injuries to incompletely developed teeth where pulp necrosis is likely and there has been damage to the external root surface and the periodontal ligament. These injuries require immediate root canal treatment as part of the emergency management of the injury in order to prevent external inflammatory resorption: (A) Intrusion WITH a crown fracture; (B) Avulsion WITH a crown fracture.

tooth, such as a first premolar, can be clamped and the dental dam can be stretched over several teeth to isolate the injured tooth or teeth.[26] This technique is quick and simple while also providing enhanced access to the tooth or teeth being treated since the clamp is placed at some distance away from the operating area (Fig. 4). The dental dam should ideally be placed prior to repositioning and splinting the tooth as it protects the airway and provides a dry field for splint placement.

After cutting an appropriate access cavity, the dental pulp can be removed with an instrument such as a barbed broach.[26] The root canal should be irrigated with an irrigant such as sodium hypochlorite or ethylenediamine tetra-acetic acid with cetrimide (EDTAC). Saline could also be used, but it has no therapeutic effect other than flushing the canal of any loose debris. After irrigating the canal, the irrigating syringe can be used to evacuate the bulk of the irrigant solution and then paper points can be used to dry the canal.[26]

If time permits, the clinician could establish the 'working length' of the canal by taking a radiograph but this is not necessary at this stage and only serves to prolong the treatment for the patient.[26] Likewise, chemo-mechanical preparation and enlargement of the root canal is not necessary at this stage as the key thing is to remove the pulp and place a medicament. The technical procedure of root canal preparation can be performed at a subsequent scheduled appointment when convenient and when sufficient time is available.[26] Since the vast majority of TDI's occur in young patients, the root canal will usually be of a reasonable size anyway and therefore there will be sufficient space available for a medicament to be placed.

The medicament of choice that has been discussed in the various publications is a corticosteroid-antibiotic

(CS-AB) paste.[26,32,40] The literature reviews in these publications outline several advantages of such a combination paste – such as, the anti-inflammatory action and the anti-resorptive activity (by inhibiting clastic cells) of the corticosteroid component, plus the antibacterial activity and the anti-resorptive activity of the antibiotic component when a tetracycline antibiotic is used.[41-43] Other antibiotics have not been shown to have the anti-resorptive activity that the tetracyclines provide. When placing the medicament, care should be taken to avoid placing and leaving any of the medicament in the crown of the tooth as this could lead to subsequent discolouration.[44,45]

Following the placement of the medicament, a suitable temporary restoration should be placed in the access cavity. After removal of the dental dam, the occlusion should be checked to ensure the tooth has been correctly repositioned in its socket and to avoid further (occlusal) trauma during the healing phase.[26,32]

Follow-up management and further root canal treatment will then need to be arranged. Tables 4 and 5 outline the recommended protocols for this, according to the stage of root development of the tooth.

The most recent[46,47] and the previous[48] International Association of Dental Traumatology (IADT) guidelines for the management of luxation and avulsion injuries provide two options for the management of teeth that have the injuries listed in Table 3 – that is, those that are likely to develop external inflammatory resorption. One option is that described above where root canal treatment is commenced immediately and a CS-AB paste is used as the intracanal medicament. The other option is to commence root canal treatment within 2 weeks and place calcium hydroxide paste as the medicament for up to 1 month before completing the root canal filling. However, this latter approach has several disadvantages and should only be followed if the clinician does not have access to a suitable CS-AB paste.

The first consideration and potential disadvantage is in waiting for 2 weeks to commence root canal treatment since the inflammatory response will have already commenced (as a result of damage to the PDL during the injury) by the time the patient seeks emergency treatment.[26,49] The inflammation is a direct result of the injury itself and therefore it commences immediately. Secondly, any bacteria that have been able to enter the root canal system during or after the injury will have that 2-week period to establish an infection within the root canal system, particularly because the pulp has lost its blood supply as part of the displacement of the tooth during the injury (i.e. the 'instant necrosis' discussed above).[24] This implies that external inflammatory resorption can commence within those first 2 weeks following the injury, as shown by Hammarström *et al.*[49] who reported that external inflammatory resorption was well established 3 weeks after a simulated avulsion injury. This strongly suggests that the resorption would be present, or at least has commenced, within the first 2 weeks as the resorptive process develops over time. Thirdly, calcium hydroxide has a degree of toxicity which is related to its mechanism of action in killing bacterial cells and inhibiting clastic cells.[43,50,51,52] However, this toxicity can also kill or inhibit the reparative cells (i.e. fibroblasts) within the PDL and this can lead to ankylosis and external replacement resorption since the healing response favours bone formation rather than PDL repair.[43,50,51,52] This response is the reason

Table 4. Recommended preventive treatment protocol for incompletely developed teeth to prevent external inflammatory root resorption after suffering the injuries listed in Table 3 (adapted from Abbott & Castro Salgado,[23] Abbott[26] and Cvek *et al.*[32]).

Incompletely developed teeth – Preventive management
- Systemic antibiotics – start IMMEDIATELY
  - Check the patient's age, weight, allergies etc. to determine appropriate systemic antibiotic and doses
  - Tetracycline preferred – for example doxycycline 100 mg – 2 tablets on the 1st day, and then 1 tablet daily for 1 week
  - Alternatively (e.g. if allergy to tetracycline), use phenoxymethyl penicillin 1000 mg immediately and then 500 mg every 6 h (1 h before meals) for 1 week, or use amoxicillin 1000 mg immediately, then 500 mg every 8 h for 1 week
- IMMEDIATELY after replantation/repositioning and stabilisation with a splint
  - Remove the pulp, irrigate and dry the root canal – if time available, measure and prepare the root canal
  - Place a CS-AB paste intracanal dressing
- After 4 weeks – complete canal preparation (if not previously done), place a new CS-AB paste intracanal dressing
- After another 4 weeks – place a new CS-AB paste intracanal dressing
- After another 4 weeks – take a periapical radiograph
  - If no inflammatory resorption evident—place a new intracanal dressing using a 50:50 mixture of CS-AB & $Ca(OH)_2$
- After 2–3 months – take a periapical radiograph
  - If no inflammatory resorption evident – place a $Ca(OH)_2$ intracanal dressing to induce formation of an apical hard tissue barrier
- Change the $Ca(OH)_2$ intracanal dressing every 3 months until hard tissue repair (e.g. apexification) is evident. Take a periapical radiograph every 6–9 months to monitor healing
- Place the root canal filling using gutta-percha and cement once the apical hard tissue barrier has formed
- Perform internal bleaching, if required
- Restore the access cavity
- Arrange to review the tooth after 6 months and then annually for at least 5 years.

The root canal treatment must be commenced as soon as the tooth has been replanted/repositioned and stabilised with a splint.
CS-AB = corticosteroid/antibiotic.
$Ca(OH)_2$ = calcium hydroxide paste.
Working length and canal preparation can be deferred until the second appointment if insufficient time available at the emergency appointment.
Dental dam must be used for all endodontic procedures.

Table 5. Recommended preventive treatment protocol for fully developed teeth to prevent external inflammatory root resorption after suffering the injuries listed in Table 3 (adapted from Abbott & Castro Salgado,[23] Abbott[26] and Cvek *et al.*[32]).

Fully developed teeth – preventive management
- Systemic antibiotics – start IMMEDIATELY
  - Check the patient's age, weight, allergies etc. to determine appropriate systemic antibiotic and doses
  - Tetracycline preferred – for example doxycycline 100 mg – 2 tablets on the 1st day, and then 1 tablet daily for 1 week
  - Alternatively (e.g. if allergy to tetracycline), use phenoxymethyl penicillin 1000 mg immediately and then 500 mg every 6 hours (1 hour before meals) for 1 week, or use amoxicillin 1000 mg immediately, then 500 mg every 8 hours for 1 week
- IMMEDIATELY after replantation/repositioning and stabilisation with a splint
  - Remove the pulp, irrigate and dry the root canal—if time available, measure and prepare the root canal
  - Place a CS-AB paste intracanal dressing
- After 6 weeks – complete canal preparation (if not previously done), place a new CS-AB paste intracanal dressing
- After another 6 weeks – take a periapical radiograph
  - If no inflammatory resorption evident—place an intracanal dressing using a 50:50 mixture of CS-AB & $Ca(OH)_2$
- After 2–3 months – take a periapical radiograph
  - If no inflammatory resorption evident – place the root canal filling using gutta-percha and cement
- Perform internal bleaching, if required
- Restore the access cavity
- Arrange to review the tooth after 6 months and then annually for at least 5 years.

The root canal treatment must be commenced as soon as the tooth has been replanted/repositioned and stabilised with a splint.
CS-AB = corticosteroid/antibiotic.
$Ca(OH)_2$ = calcium hydroxide paste.
Working length and canal preparation can be deferred until the second appointment if insufficient time available at the emergency appointment.
Dental dam must be used for all endodontic procedures.

for the recommendation to wait for 2 weeks before placing calcium hydroxide. Hence, waiting for 2 weeks is problematic in that the resorptive process may have already commenced which means that it will then need to be arrested and any lost tissue may not be replaced because of the irritant effect of the calcium hydroxide.[43,50,51,52] Therefore, if the clinician has access to a CS-AB paste (particularly one containing a tetracycline), then immediate commencement of root canal treatment and placement of this paste is the preferred approach.[23,26,40] If the clinician does not have access to a CS-AB paste, then the second option of waiting 2 weeks and placing $Ca(OH)_2$ is recommended.[46-48]

Immediate commencement of root canal treatment in the above situation has some other advantages related to management of the patient. Firstly, the patient is already present in the dental chair and the tooth and surrounding tissues should have been anaesthetised prior to repositioning/replanting the tooth, stabilising it with a splint and suturing any lacerations.[23] Secondly, dental dam should ideally have been placed prior to the repositioning/replanting and stabilisation of the tooth.[23] Hence, the situation is ideal for the immediate commencement of root canal treatment. Thirdly, the patient does not need to return for an additional appointment at a time when the tissues are still healing (i.e. within the first 2 weeks after the injury) and the patient (and/or the parents if the patient is a child) will not have the opportunity to become apprehensive about having root canal treatment which is potentially likely with a delay in commencement of this procedure. Unfortunately, the public perception of root canal treatment is not ideal and many patients are apprehensive about experiencing pain during this treatment.[53] Fourthly, typically after injuries to the teeth and oral region, there is very likely to be swelling of the lips and this can hinder access to the teeth, as well as being very uncomfortable for the patient, if a delayed approach to commencing root canal treatment is adopted. Finally, there is the possibility that the patient may not return at the appropriate time for the treatment to be commenced. This may occur for a variety of reasons including apprehension, ongoing discomfort associated with the injured tooth/teeth and cost concerns. If the patient does not return at the appropriate time, then the external inflammatory resorption will progress, and this results in the loss of more tooth structure. In young patients, the resorption can progress extremely quickly because there is less tooth substance to resorb. This is a result of the root canal being wider, less dentine between the canal and the cementum, and the dentine tubules are wider. All of these factors may mean the resorption advances to the point where treatment is unlikely to arrest the resorption and/or the tooth will have a very poor prognosis due to the lack of root dentine even if the resorption can be controlled.

As mentioned above, systemic antibiotics are also recommended as part of the preventive management of teeth with the injuries listed in Table 3. The preferred antibiotic is doxycycline, which is a synthetic tetracycline. Doxycycline is preferred because tetracyclines have a secondary action of inhibiting clastic cell activity in addition to their antibacterial activity.[42] A further advantage of tetracyclines is the binding of the drug to the dentine and bone which keeps it at the site of required action for a longer period of time than other antibiotics.[42,54,55] Doxycycline is the preferred tetracycline because it does not cause staining of the teeth and therefore it can be used in patients of any age.[56,57] This is an advantage since most TDI's occur in young children.[38]

Many practitioners may be concerned about the use of doxycycline in young children because of the risk of tooth discolouration associated with tetracyclines.

However, this is not a concern for doxycycline as many studies have shown that doxycycline does not stain the teeth.[58] This is likely a result of its reduced binding with calcium (19%) compared to tetracycline (39.5%) and demeclocycline (74.5%),[59] plus its daily therapeutic dose is a tenth of that of tetracycline hydrochloride.[60] Studies have reported no visible tooth staining, no enamel hypoplasia and no tooth colour differences in children aged less than 8 years old when treated with doxycycline for several diseases such as Rocky Mountain Spotted Fever[57] and malaria[56] compared to children who had never received doxycycline. The use of short-term doxycycline in children under 8 years of age has been advocated by many authors[56,57,61,62,63,64,65,66,67] as well as the US Centers for Disease Control and Prevention.[68,69] In the Australian context, expert groups have advised that doxycycline is unlikely to stain teeth in children aged less than 8 years old when used for short terms up to 21 days and they recommend that doxycycline should be used when it is the drug of choice regardless of the patient's age.[70] Hence, the use of doxycycline for the seven days recommended as part of the management protocol to prevent external inflammatory resorption[26,32,40] is unlikely to cause tooth discolouration.

Root canal treatment later during follow-up of a TDI

All TDI's that are not listed in Table 2 do NOT require immediate root canal treatment as part of the emergency management of the tooth following a TDI. A full list of these injuries is provided in Table 6. The pulps of these teeth should be monitored on a regular basis with a thorough clinical examination, pulp sensibility tests and periapical radiographs to assess the state of the pulp and the root canal system.[46,47,71,72] Root canal treatment should only be considered and commenced when there are definitive signs of pulp necrosis AND infection of the root canal system. Definitive signs of infection include pain, swelling, apical periodontitis, periapical radiolucency, external inflammatory resorption and/or a draining sinus.[23,24,26,73] Root canal treatment should only be considered when one or more of these signs are present.[32,73,74]

When reviewing teeth following TDI's, the use of cold and electric pulp sensibility tests is essential.[32] However, the results of these tests must be interpreted with caution as these tests are only assessing the ability of the pulp to respond to the stimulus that is applied to the external surface of the tooth – that is, the cold source or the electric current.[74-77] Hence, they assess the neural response but not the presence or absence of blood supply to the pulp. If a tooth does respond to a pulp sensibility test, an assumption is then made that the pulp is likely to have a viable blood supply. Conversely, if there is no response to the sensibility tests, then it is generally assumed that there is no blood supply, in which case the pulp may be necrotic or the tooth may be pulpless. However, these assumptions are not always valid, especially in the first few months following a TDI. It is well known that the nerve fibres take a longer time than the blood vessels to recover throughout the full length of the pulp space and therefore a tooth that does not respond to pulp sensibility tests may actually have a blood supply which renders the pulp as viable (Fig. 1) and likely to survive.[74-77] It is also well known that some teeth may respond to an electric pulp test at an earlier review period than the cold test, and *vice versa*. Responses may also vary at each review appointment (Fig. 3) Hence, it is essential to use both cold and electric pulp sensibility tests when reviewing teeth that have been traumatised since if only one test is performed, it may be the test that does not produce a response and the clinician may be misled in thinking that the pulp has necrosed. Pulp sensibility tests should also always be interpreted in conjunction with a thorough clinical examination and other tests (such as percussion, palpation, periodontal probing, mobility, etc.) and the radiographic appearance of the periradicular tissues.[74]

Clinicians should also be aware of the possibility of transient apical breakdown (TAB). This phenomenon was first described by Andreasen[78] and it occurred in 4.2% of the cases examined in that study. Most of the

Table 6. Injuries where root canal treatment is NOT required as part of the emergency management of the tooth.

Injuries where immediate root canal treatment is *NOT* Indicated	
Incompletely developed teeth	Fully developed teeth

• Crown infraction
• Uncomplicated crown fracture
• Uncomplicated crown-root fracture
• Root fractures
  ◦ Apical third
  ◦ Middle third
  ◦ Sub-crestal coronal third root fracture
• Concussion
• Subluxation
• Extrusion
• Lateral luxation
• Intrusion (with no crown fracture)
• Avulsion (with no crown fracture)
	• Crown infraction
	• Uncomplicated crown fracture
	• Uncomplicated crown-root fracture
	• Root fractures
	  ◦ Apical third
	  ◦ Middle third
	  ◦ Sub-crestal coronal third root fracture
	• Concussion
	• Subluxation
	• Extrusion (with no crown fracture)
	• Lateral luxation (with no crown fracture)

The pulps of these teeth should be monitored on a regular basis with a thorough clinical examination, pulp sensibility tests and periapical radiographs to assess the state of the pulp and root canal system. Root canal treatment should only be commenced when there are definitive signs of pulp necrosis AND infection of the root canal system – such as, pain, swelling, apical periodontitis, external inflammatory resorption and draining sinus.

teeth had fully developed roots. TAB is considered to be a spontaneous repair process that may be seen following relatively mild injuries such as subluxation, extrusion or lateral luxation.[78] It has been hypothesised that this process is the body's way of promoting revascularization of the pulp after the vascular supply has been severed or reduced as a result of the injury. TAB occurs within the first few months following injury. The tooth appears to have a periapical radiolucency and the apical end of the root appears as though it is resorbing. The crown of the tooth may have some discolouration and the pulp may or may not respond to cold and electric pulp sensibility tests.[78,79] Hence, this condition can be easily misdiagnosed as external apical inflammatory resorption. However, over the ensuing months (usually about 3–6 months), the tooth begins to respond to the pulp sensibility tests, the crown colour returns to normal and radiographs show healing of the periapical radiolucency along with remodelling of the root apex. Over further time, radiographs will usually also show narrowing of the root canal as a result of pulp canal calcification along with closure of the apical foramen.[78,79] An example of a tooth that had TAB is provided in Figure 9.

TAB is difficult to definitively diagnose and to differentiate from external apical inflammatory resorption. In essence, the diagnosis is somewhat retrospective and can only really be confirmed once the healing processes outlined above are evident. If the tooth is responding to pulp sensibility tests, then the clinician can be more certain of the diagnosis. However, if there are no responses to the pulp tests, and assuming there are no symptoms to suggest an infected root canal system, then the clinician should assume it is TAB and closely monitor the tooth for repair. No treatment is required for TAB apart from close monitoring on a regular basis.[78]

As discussed above, pulp necrosis will not always be associated with an infected root canal system. Pulp necrosis may be a result of severing of the apical blood supply during an injury, such as a luxation or avulsion. Hence, some teeth may actually have a necrotic pulp but no bacteria within the root canal system.[80-82] Such teeth do not require root canal treatment since apical periodontitis only develops once the necrotic pulp becomes infected.[80-82] However, these teeth do need to be monitored as the necrotic pulp could become infected over time, especially if there is an entry pathway for bacteria to reach the pulp, such as an infraction, a restoration breaking down or caries.[74] As above, definitive signs of pulp necrosis AND infection of the root canal system include pain, swelling, apical periodontitis, periapical radiolucency, external inflammatory resorption and/or a draining sinus. Root canal treatment should only be considered when one or more of these signs are present.[32,73,74]

Follow-up schedule

Close monitoring of traumatised teeth in the first few months is essential since most unfavourable sequelae associated with the pulp and root canal system following TDI's develop within the first 12 months of the injury occurring.[24,25,32,46,47,71-73,83-86] Pulp necrosis and infection of the root canal system will often become evident within the first 3-4 months as does external inflammatory resorption.[73] Other complications such as ankylosis and replacement resorption that are not related to the pulp are usually evident with the first 6–12 months.[24,25,32,46,47,71,72,73,83,84,85,86]

The recommended follow-up schedule can vary for the different injuries, depending on their severity and the stage of root development.[71,72] A general guide is provided in Table 7. However, clinicians may need to modify this schedule, depending on the individual tooth and its injury, the presence of other TDI's, the stage of root development, patient convenience, etc.

Each follow-up appointment should include a thorough clinical examination and all of the usual diagnostic tests such as both cold and electric pulp sensibility tests, percussion, palpation, periodontal probing, mobility and periapical radiographs.[71,72,74] Transillumination is also a very useful test to assess the tooth for the presence and extent of infractions and cracks as well as any changes over time.[74] Clinicians should be aware that pulps may give variable responses to cold and electric pulp sensibility tests throughout the review period, and especially within the first 3–6 months, or even longer in some cases (Fig. 3). As discussed above, the lack of response to a pulp test does not necessarily mean that the pulp has necrosed and other definite signs of infection of the root canal system should be present before considering root canal treatment.

The International Association for Dental Traumatology has published a core outcome set (COS) that should be utilised when reviewing teeth that have suffered traumatic dental injuries.[72] This COS provides comprehensive information about the various potential outcomes of each type of TDI. The outcomes are grouped as 'generic' (that is relevant to all TDI's) and 'injury-specific' (related to one or more particular TDI's) outcomes. The COS also outlines what should be assessed, how and when they should be assessed, and by whom.[71,72]

Clinical photographs should be taken on a regular basis to monitor the colour of the tooth as discolouration may be associated with pulp haemorrhage and/or pulp necrosis.[87,88] Discolouration associated with pulp haemorrhage usually occurs very soon after the injury and causes a grey stain which often resolves over time as the pulp revascularizes and recovers. In contrast, discolouration as a result of pulp necrosis usually develops some time after the injury – for example,

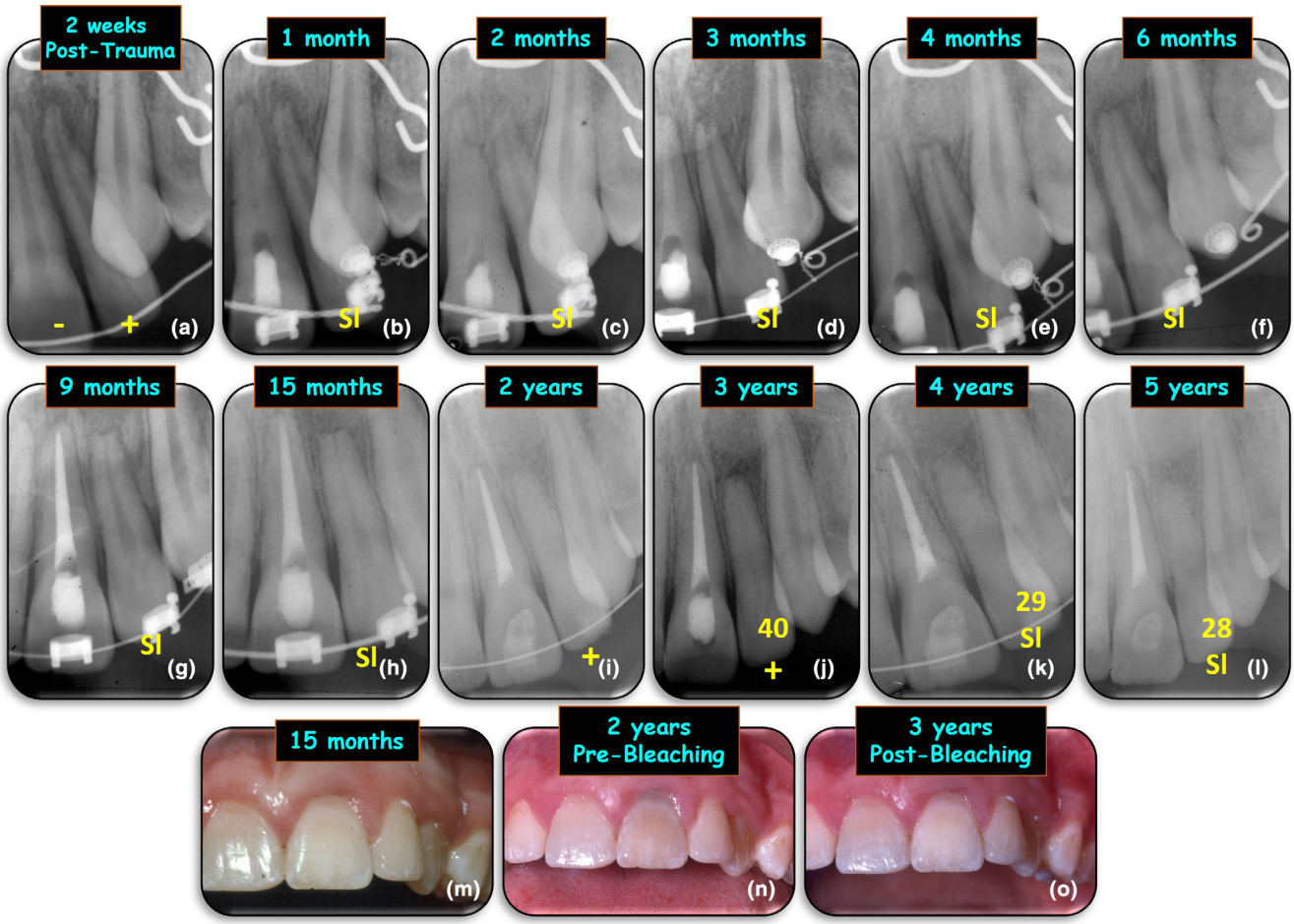

Fig. 9 Example of a tooth that had transient apical breakdown. The maxillary left central and lateral incisors (teeth 21 and 22) of a 14-year-old male were laterally luxated when he fell off his bicycle. The two teeth were repositioned and splinted by his orthodontist approximately two hours after the accident. Two weeks later, the 21 had pain and swelling indicating pulp necrosis and an infected root canal system so root canal treatment was commenced. The 22 was monitored with regular clinical examinations, pulp testing and radiographs. The 22 responded slowly (compared to other teeth) to carbon dioxide dry ice pulp sensibility testing and there were radiographic signs of remodelling of the apex of the root, including opening of the apical foramen before it subsequently closed again. The periapical region also showed changes with a radiolucency which subsequently resolved, indicating transient apical breakdown. The pulp also underwent pulp canal calcification. The 21 was root-filled after 9 months of intracanal medication to prevent external inflammatory resorption. It was subsequently internally bleached as the crown discoloured. (a) 2 weeks after the injuries occurred; (b) Review after 1 month; (c) Review after 2 months; (d) Review after 3 months; (e) Review after 4 months; (f) Review after 6 months; (g) Review after 9 months; (h) Review after 15 months; (i) Review after 2 years; (j) Review after 3 years; (k) Review after 4 years; (l) Review after 5 years; (m) Clinical appearance 15 months after the injury; (n) Clinical appearance 2 years after the injury; the 21 has discoloured; (o) Clinical appearance 3 years after the injury and following internal bleaching of the 21. Footnote – KEY: yellow numerals represent results of electric pulp tests (scale 1–80); yellow '+' sign indicates the tooth responded to carbon dioxide dry ice testing; yellow text 'Sl' indicates a slow response to the carbon dioxide dry ice test (compared to other teeth); yellow '-' sign indicates no response to the carbon dioxide dry ice test.

1–3 months later as this is when pulp necrosis and infection usually become evident. The discolouration from pulp necrosis is usually a yellow or dark yellow stain, but it could also be a grey stain if there had been pulp haemorrhage prior to the necrosis.[87,88]

Specific findings to observe and assess at follow-up examinations are the responses to the various tests as well as the radiographic appearance. In particular, periapical radiographs should be assessed for the following changes:

- Incompletely developed teeth
  - Pulp canal calcification (PCC) – this will appear radiographically as narrowing of the pulp chamber, root canal and pulp space. Over time, this narrowing of the pulp space increases and eventually the entire root canal may appear to be calcified when assessed radiographically. However, histologically, and usually clinically, a very narrow canal space will remain. PCC is a normal, physiologic response of the pulp and in the absence of any unfavourable findings (such as a periapical radiolucency, external inflammatory resorption, swelling or a draining sinus), it should be interpreted as a very definite indication that the pulp has survived and it is functioning normally.[23,24,32,72,85,89,90]

Table 7. Recommended follow-up schedule for traumatic dental injuries that do not require immediate root canal treatment.

Follow-up schedule for traumatic dental injuries where immediate root canal treatment is not required
• 1 week
• 2 weeks
• 4 weeks (i.e. 1 month)
• 2 months
• 3 months
• 6 months
• 9 months
• 12 months (i.e. 1 year)
• Annually for 5 years
• Then every 3–5 years (for as long as possible)

This schedule may need to be modified according to the severity of the injuries, the stage of root development, injuries to other teeth or tissues, the timing of suture removal, the timing of splint removal, patient convenience, etc.
All times are times from when the injury occurred.
Assume there are no adverse findings discovered at each follow-up examination.

  - Further root development – radiographically, the root will be longer than when first observed after the injury and the apical foramen will become narrower, along with narrowing of the root canal space (PCC). These are all positive signs that the pulp has recovered and is functioning normally.[23,24,32,72,89,90] Conversely, if the root does not continue to develop, then pulp necrosis should be suspected in which case, the clinician should determine whether the root canal system has become infected. If there is an infected root canal system, then root canal treatment will be required.[32]
- Incompletely and fully developed teeth
  - Periapical radiolucency – in the absence of symptoms, this indicates that there is chronic apical periodontitis. If symptoms are present, then it typically indicates acute apical periodontitis. In some cases, the apical periodontitis may have progressed to become an apical abscess. If there is swelling present, then it will be an acute apical abscess. If there is no swelling but there is a draining sinus that tracks to the radiolucency, then the abscess will be a chronic apical abscess. These periapical conditions develop as a result of pulp necrosis and infection of the root canal system. The tooth will not respond to pulp sensibility tests and there may be other signs such as pain or tenderness on percussion and/or palpation.[23,24,89,90,91]
  - External inflammatory resorption – as outlined above, there will be radiolucencies within the tooth root indicating loss of tooth substance together with radiolucencies in the bone adjacent to the areas of tooth substance loss. This type of resorption indicates pulp necrosis and infection of the root canal system.[23,26,32,40,89,90,91]

Teeth with PCC and/or where further root development has occurred do not require root canal treatment or any other intervention. They simply need to be monitored over time to assess whether any unfavourable responses or other adverse events subsequently develop.[23,24,72]

Teeth with a periapical radiolucency and/or external inflammatory resorption require root canal treatment and this should ideally be commenced as soon as the condition has been diagnosed.[23,26,32,89,90,91] The aims of treatment will be largely to disinfect the root canal system but also to encourage hard tissue repair of the cementum and bone where tissue has been lost.[23,26,32,40] Once healing has been confirmed, the root canal filling and definitive restoration of the coronal aspect of the tooth should be completed with the aim to prevent re-infection of the root canal system in the future. In the case of external inflammatory resorption, the interceptive treatment protocol should

Table 8. Recommended interceptive treatment protocol for teeth where external inflammatory resorption is occurring (adapted from Abbott & Castro Salgado,[23] Abbott[26] and Cvek *et al.*[32]).

Interceptive management
• Remove all restorations, caries and cracks from the tooth; ensure the tooth is suitable for root canal treatment and restoration.
◦ If unsuitable for restoration, extract the tooth
◦ If suitable for treatment, gain access to the root canal system
• Negotiate the root canal, measure working length and chemo-mechanically prepare the root canal; irrigate thoroughly and dry the canal
• Place a CS-AB paste intracanal dressing
• After 6 weeks – place a new CS-AB paste intracanal dressing
• After another 6 weeks – take a periapical radiograph
◦ If the inflammatory resorption has not progressed – place a new intracanal dressing using a 50:50 mixture of CS-AB & $Ca(OH)_2$
• After 2–3 months – take a periapical radiograph
◦ If the inflammatory resorption has not progressed – place a $Ca(OH)_2$ intracanal dressing – to induce hard tissue repair
• Change the $Ca(OH)_2$ intracanal dressing every 3 months until hard tissue repair of the resorptive lesion is evident. Take a periapical radiograph every 6–9 months to monitor healing and to determine when the root canal filling can be completed
• Once hard tissue repair is evident, place the root canal filling using gutta-percha and cement
• Perform internal bleaching, if required
• Restore the access cavity
• Arrange to review the tooth after 6 months and then annually for at least 5 years.

CS-AB = corticosteroid/antibiotic.
$Ca(OH)_2$ = calcium hydroxide paste.
Dental dam must be used for all endodontic procedures.
Systemic antibiotics are NOT indicated, unless the patient has systemic signs (i.e. malaise, increased body temperature, lymph node involvement, rapid spreading infection, etc.) of a systemic infection associated with the tooth (e.g. secondary acute apical abscess or facial cellulitis).

be adopted, as described in other publications.[23,26,32] A summary of this protocol is provided in Table 8.

CONCLUSIONS

The dental pulp can have various favourable and unfavourable responses following traumatic dental injuries. The most serious unfavourable responses are pulp necrosis and infection of the root canal system as these can lead to apical periodontitis and/or external inflammatory resorption. It is essential that dentists have a thorough understanding of the various responses so the inclusion of root canal treatment as part of the emergency management of the injury should only be provided when it is truly necessary or as a preventive measure to avoid complications. Fortunately, most traumatic dental injuries do not require immediate root canal treatment as part of the emergency management of the tooth. In such cases, it is imperative that these teeth are reviewed regularly, especially during the initial 3-6 months following the injury, since pulp necrosis and infection may occur as a longer-term consequence of the injury.

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AUTHOR CONTRIBUTIONS

Paul V. Abbott: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration.

CONFLICTS OF INTEREST

Prof. Abbott is occasionally paid an Honorarium for consulting and/or lecturing work for OzDent Dental Products Australia, the suppliers of Ledermix Paste, Calasept Plus and Calmix. Prof Abbott declares that he has no other conflicts of interest with respect to this review article.

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Address for correspondence
Paul V. Abbott
UWA Dental School
The University of Western Australia
17 Monash Avenue
Nedlands
WA
6009
Australia.
Email: *paul.v.abbott@uwa.edu.au*